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PRINCIPLES OF CONSTRUCTION

IN

ARCHES, PIERS, BUTTRESSES

&c.

USEFUL TO THE PRACTICAL BUILDER.

BY WILLIAM BLAND, Esq.

108 *Illustrations.*

LONDON:—JOHN WEALE.

ON THE

PRINCIPLES OF CONSTRUCTION

IN

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EXPERIMENTAL ESSAYS

ON THE

PRINCIPLES OF CONSTRUCTION

IN

ARCHES, PIERS, BUTTRESSES,

&c.

MADE WITH A VIEW TO THEIR BEING USEFUL TO THE

PRACTICAL BUILDER.

By WILLIAM BLAND, Esq.

NEW EDITION.

LONDON:
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1862.

PREFACE.

The Public having given proof of its approval of this small work by the purchase of every copy some time since, the application for more has induced the Author to provide a Second Edition.

The pages of the former work have been carefully revised and corrected preparatory to the New Edition, which the Author hopes will prove satisfactory.

W. B.

CONTENTS.

ESSAY I.

ESSAY II.

ESSAY III.

ESSAY IV.

ESSAY V.

ESSAY VI.

ESSAY VII.

ESSAY VIII.

ESSAY IX.

ESSAY X.

ESSAY XI.

EXPERIMENTAL ESSAYS.

ESSAY I.

ARCHES.

The Principles of Arches.—Being fond of architecture, particularly that branch of it which relates to bridges and cathedrals, I have been induced to investigate the principles by which such stupendous, beautiful, and lasting fabrics were, and still are, constructed. I have examined the pages of Hutton, Atwood, Ware, the Encyclopædias, and others, on my favourite subject; but, failing in my object, after a careful perusal of them, I was necessitated to investigate for myself. I have done so, and this and the following essays contain the result of my inquiries, which I humbly and respectfully lay before the public, in order that it may judge of their accuracy; and, also, to afford an interest to those persons who are of a corresponding taste with myself.

My first step was to cut out a quantity of wooden bricks for voussoirs, or arch stones, 4 in. long, 2½ in. deep, and 2 in. thick, sufficient in number to construct two semicircular arches; one of 10 in. span, the other of 24 in. Besides these, I cut out about 300 wooden bricks, 4 in. long, 2 in. wide, and 1 in. thick. With these materials, and without cement, I was enabled to erect arches of various forms and dimensions; but, still, a knowledge of the true principles on which they should be constructed continued to elude me

and to remain unknown. I, however, discovered that all arches, of whatever form they might be, were subject to the laws of two distinct forces; namely, one acting perpendicularly downwards, and the other horizontally outwards. This being the case, I determined to ascertain, as accurately as I could, by means of weights, the exact proportion in which these two forces acted upon every voussoir throughout an entire semicircular arch, and for this purpose I had recourse to the following plan.

I constructed a frame, as represented by fig. 1, the form

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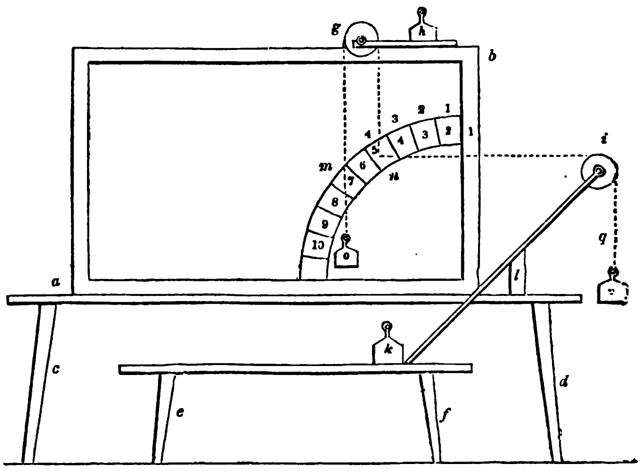

of an oblong parallelogram (*a b*), and placed it on the edge of a table (*c d*), under which was a stool (*e f*). Two movable pulleys were attached to the frame; one at the top at *g*, which was kept in its place by the weight *h*; and the other (*i*) resting on one end of the stool, and having a weight (*k*) to prevent it from slipping; with the support *l*, at *d*, to raise or depress it at pleasure. A proportion of an arch of the semicircular form, to be experimented upon, is represented at *m n*, and consists of ten voussoirs; the fourth of

which (n) is in the act of trial, and has the perpendicular force of the voussoirs 1, 2, 3, balanced by the weight o, which is attached to the line $m\ g\ n$, running over the pulley g; and the horizontal force of the same voussoirs is balanced by the weight p, attached to the line $g\ i\ n$, running over the pulley i. The fourth voussoir itself is considered as having no weight in these trials, because it just counteracts the weight of the scales and lines.

With this apparatus I succeeded in the measurement of the perpendicular and horizontal forces; in consequence of which I put the voussoirs to every kind of test, and found that a corresponding law takes place throughout, relative to these two forces, which led me easily to construct a curve above that of the semicircular curve, commonly called the extrados, to represent the lateral or horizontal forces proportional to each respective voussoir, throughout the whole of the arch of the semicircular form. The perpendicular forces, being resisted by the foundation on which every arch must stand, need not be taken into consideration in the construction of the curve; but these perpendicular forces, which are proportional to each and every voussoir, can be represented better in a diagram without a curve; by which means the diagonal lines can be drawn to exhibit the proportions of the compound of the two forces, the perpendicular and horizontal, on every part of the semicircular arch. The following are the results of my experiments: —

Experiment First, made with only half of the arch, consisting of ten voussoirs. Let $m\ n$ (fig. 2) be the half of the arch, and constructed of ten voussoirs, from 1 to 10; and g, the perpendicular pulley, with the string and weight o; i, the horizontal pulley, with the string and weight p: the following are the results, beginning with No. 1, and descending to No. 10, taking away each voussoir after ascertaining the two forces.

No. 1 has a perpendicular pressure of $\frac{1}{4}$ of a pound, and a horizontal pressure of $\frac{3}{4}$ of a pound.

No. 2 has a perpendicular pressure of $\frac{1}{8}$ of a lb, and a horizontal weight, or pressure of $\frac{11}{16}$ of a lb.

No. 3 has no perpendicular pressure, but $\frac{1}{2}$ of a lb of horizontal weight.

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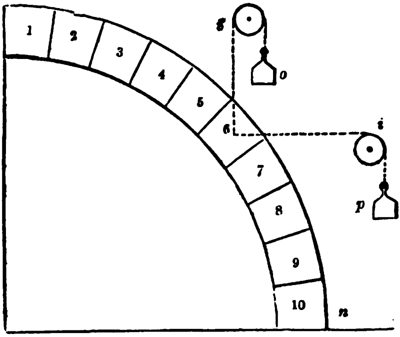


No. 4 has no perpendicular pressure, but $\frac{1}{4}$ of a lb of horizontal weight.

No. 5 has no perpendicular pressure, but is sustained by a horizontal force of $\frac{1}{8}$ of a lb.

No. 6 has no perpendicular pressure or horizontal force, the friction of the pulleys being sufficient to retain it in its place.

No. 7, 8, 9, 10, stood alone on each other.

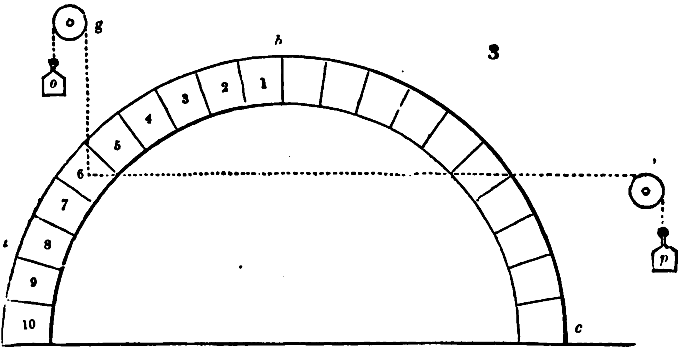
Experiment Second, made with the whole semicircular arch, consisting of twenty voussoirs. Let *a b c* (fig. 3) be the arch; *g* and *o*, the pulley and weight to measure the perpendicular force; and *i p*, the pulley and weight to measure the horizontal force. In this experiment the voussoir No. 1 was placed against the part of the arch *b c*, as represented in the diagram, and the two forces then measured; the voussoir No. 2 against No. 1 and *b c*; and so on to No. 10. The results are as follows: —

No. 1 has a perpendicular weight of $\frac{1}{2}$ of a lb, and a horizontal force of $1\frac{1}{4}$ lb.

No. 2 has a perpendicular weight of $\frac{3}{4}$ of a lb, and a horizontal force of $1\frac{1}{2}$ lb.

No. 3 has a perpendicular weight of 1 lb, and a horizontal force of $1\frac{5}{8}$ lb.

No. 4 has a perpendicular weight of $1\frac{3}{8}$ lb, and a horizontal force of $1\frac{5}{8}$ lb.



No. 5 has a perpendicular weight of $1\frac{5}{8}$ lb, and a horizontal force of $1\frac{3}{4}$ lb.

No. 6 has a perpendicular weight of 2 lb, and a horizontal force of $1\frac{7}{8}$ lb.

No. 7 has a perpendicular weight of $2\frac{1}{2}$ lb, and a horizontal force of $2\frac{1}{8}$ lb.

No. 8 has a perpendicular weight of $3\frac{1}{8}$ lb, and a horizontal force of 2 lb.

No. 9 has a perpendicular weight of $3\frac{3}{4}$ lb, and a horizontal force of $1\frac{1}{2}$ lb.

No. 10 has a perpendicular weight of 4 lb, and a horizontal force of 1 lb.

By this scale of proportions belonging to experiment second, it is seen, that the perpendicular weight, or force, increases as the weight is added; but the lateral weight, or horizontal force, increases only as far as the seventh voussoir, and then decreases. From this scale, a curve, called the extrados, may be drawn above a semicircular arch,

which will exhibit pretty correctly the proportions of the lateral, or horizontal, force of every voussoir composing the arch. With regard to the perpendicular forces, it may be remarked, that, as they are resisted by the ground, or foundation, it is unnecessary to introduce them here. In fact, if diagonal lines be drawn, equalling the respective perpendicular and horizontal forces of every voussoir, each diagonal line would again be resolved into the above two horizontal and perpendicular forces, of which the one representing the latter would be omitted, in consequence of its having no tendency whatever to press outwards: but more of this hereafter.

In order to illustrate this particular relative to the extrados, let fig. 4 be a diagram, in which they are represented

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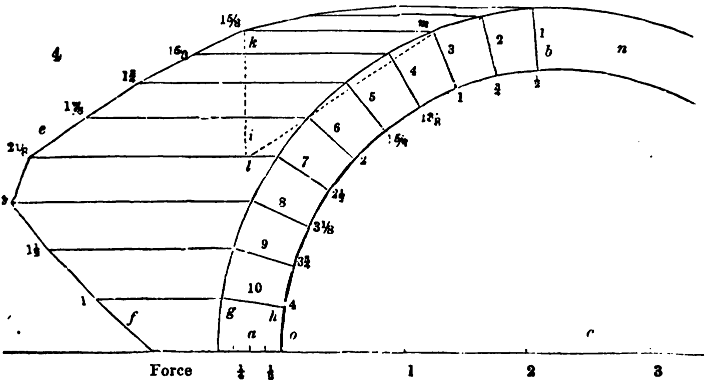


by the lines *d e f*. The figures along those lines show the horizontal forces in pounds, and the figures from *a* to *b* denote the perpendicular forces in pounds. In this diagram *a b* represents one half of an arch of 24 in. in diameter, and constructed of ten wooden voussoirs upon which the experiments were made. The thickness of the voussoirs, from *g* to *h*, is 2½ in.; and, as each voussoir weighs half a pound, I have taken the thickness of them as my scale for half a pound, which scale is divided into eighths, quarters,

halves, and whole pounds. To the adoption of this scale for half a pound I think there can be no possible objection, because, if the voussoirs were of stone instead of wood, or even of iron, this line would represent certain weights within the extrados. This being the case, the ten parallel and horizontal lines, contained within *d e f*, represent correctly the proportions of the horizontal forces acting on each of the surfaces of the ten voussoirs, numbered from 1 to 10. A line then drawn, passing through the outer extremities of the lines representing the horizontal forces, becomes the extrados to the arch of a semicircle. The figures at the end of each parallel line on the extrados denote the weights, or forces, of equilibrium outwards; and the figures under the intrados are the weights, or forces, of the equilibrium perpendicularly downwards, for each of the ten voussoirs, but the lines are not drawn.

The point *i* is the centre of gravity of the quadrant and extrados, or of the whole body comprehended within the extrados and intrados *o f e d*, which was ascertained by a model; in fact, by a piece of paper cut in the exact form of the diagram. Indeed, supposing the mass to be of a uniform thickness, and of the same specific gravity, a model of wood, stone, metal, or even of paper, will give the same precise result, and this model would just be balanced firmly on the base line, *f o*; consequently, the other half of the arch would be balanced the same; and both halves being placed together to complete the whole arch, either half would be balanced upon a foundation, or pier, of any height.

To prove that the perpendicular lines need not be represented in the diagram, although, to explain the reason, it is necessary to introduce one line, draw through the point *k* the dotted straight line *k l* perpendicular to *k m*, and equal to one pound as taken from the scale, which is the amount of the perpendicular force of the third voussoir, and join *m l*. Now, according to the law of the composition and resolution of forces, *m l* represents the two forces *m k* and *k l*,

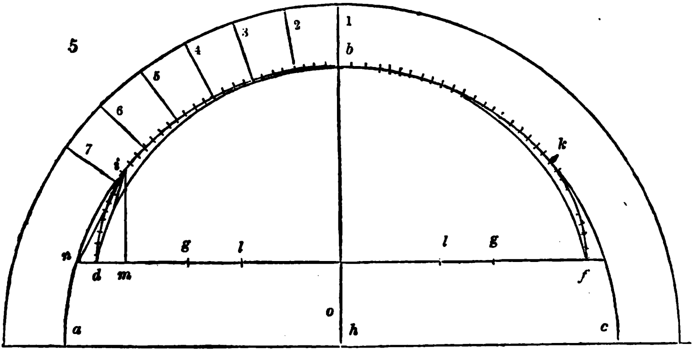
as also the force at voussoir No. 3, which equals the accumulated forces added to it of Nos. 1 and 2, and the half part of the arch not represented in the diagram. Since *m k* represents and equals the thrust of the arch at No. 3, it may be resolved into the two directions *m k* and *k l*; but the part of the thrust *k l* acts perpendicularly downwards, and, therefore, has no tendency to overthrow the arch. The part of the thrust *m k*, however, acts horizontally outwards, and, consequently, is the only overturning force of the arch at voussoir No. 3; therefore, the only part of the force *m l* which need be considered: the same may be shown of all the other horizontal lines in the diagram. On a reinspection of the diagram, it will be seen that the average distance from the extrados to the intrados, measured horizontally, equals half the span of the arch, or *o* to *c*, which is the radius of its circle.

Thus far with regard to the circular curve; and, since arches are constructed of other forms, derived from curves called the conic sections &c., such as the ellipse, the parabolic and the hyperbolic, the cycloid and the catenarian forms.

First, of the Elliptic Curve and Arch. — This curve, in its construction, approaches so near to the segments of two circular curves, as may be seen by fig. 5, that the law of the horizontal and perpendicular forces in the circular curve will almost correctly apply to the elliptic form. In the diagram fig. 5, *a b c* is a semicircular arch, and *d b f* is an ellipse, which is denoted by the dotted line; *g g* are the foci; *h*, the centre of the large circle segment *i k*; and *l l* are the centres of the small circle segments *d i* and *f k*.

In consequence of the part of the elliptic curve *i b k* so nearly coinciding with the curve of the circle, as instanced in the diagram, the lateral, or horizontal, and perpendicular forces, considered in an architectural point of view, must be the same very nearly in both. With this being granted, there remains to be considered that part only of the ellipse

which is comprehended between *d i* and *f k*. Now, in the diagram of the extrados, it is shown, that the greatest lateral force is exerted at the seventh voussoir, or at the points *i* and *k*; consequently, a counteracting buttress must be



placed at these points to preserve the structure. In the first experiment with the voussoirs, it is shown, that the four bottom voussoirs have no apparent lateral force, when the voussoirs above them have been removed; therefore, when buttresses are applied at the points *i* and *k*, or the extrados completed to counteract the outward and horizontal forces of the voussoirs above, the lowest four voussoirs on each side of the circular arch perform only the part of piers.

Since piers are for the purpose of supporting perpendicular pressure, the nearer their line approaches to the perpendicular, the more efficient they will become.

In the case before us, from the point *i* draw *i m* perpendicular to *d f*, and join *i d* and *i n*. The part *m d* of the line *m n* is less than (*m n*) the whole line; therefore the line *i d* is nearer to *i m* than to *i n*; consequently, the voussoirs of the elliptic arch between *i d* and *f k*, when those above them have their requisite abutments, become, indeed, more efficient as piers than even those of the circular arch. The conclusion we then arrive at is, that the circular and

elliptic arches, in practical architecture, have the same extrados, since the upper portion of an ellipse may be considered as a segment of a circle.

A segment of a circular arch, of the same rise and span as that of an elliptic arch, requires less extrados than the elliptic form, for this reason. In the diagram fig. 5, the segment of a circle (*d b f*) is described, passing through the points *d b* and *f*, and having its centre at *o*. Now, *o b* is the radius of the segment (*d b f*) of the circle, and *h b* is the radius of the segment of the circle of the ellipse (*i b k*); but *o b* is less than *h b*, therefore the circle is also less, and, consequently, the extrados would not be required to extend so far, which was to be shown.

Of the Parabolic Arch.—In the diagram fig. 6, *a b c* is a parabolic arch of eighteen voussoirs; *a d b c* is a semi-

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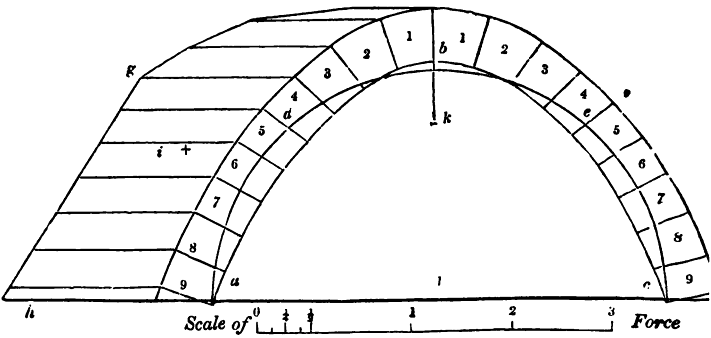

circular curve of the same span; *f g h* are the extrados to half of the parabola, from *a* to *b*; *i* is the centre of gravity; and *k* is the focus of the parabola. In the experiment with this form of arch, the following are the results of the forces of the voussoirs, beginning with the first voussoir at *b*, and ending with the ninth voussoir at *a*:—

No. 1 has a perpendicular weight of $\frac{5}{8}$ of a lb, and a horizontal force of $1\frac{1}{2}$ lb.

No. 2 has a perpendicular weight of 1 lb, and a horizontal force of $1\frac{3}{4}$ lb.

No. 3 has a perpendicular weight of $1\frac{3}{8}$ lb, and a horizontal force of $1\frac{7}{8}$ lb.

No. 4 has a perpendicular weight of $1\frac{5}{8}$ lb.

No. 5 has a perpendicular weight of $2\frac{1}{8}$ lb.

No. 6 has a perpendicular weight of $2\frac{3}{4}$ lb.

No. 7 has a perpendicular weight of 3 lb.

No. 8 has a perpendicular weight of $3\frac{3}{8}$ lb.

No. 9 has a perpendicular weight of $3\frac{7}{8}$ lb; and the horizontal force of each voussoir, from No. 4 to No. 9, is $1\frac{7}{8}$ lb.

The principal difference between the lateral, or horizontal, forces of the circular and parabolic curve is, that the lateral force of the former increases from No. 1 to No. 7 voussoir, then decreases: but the horizontal force of the latter increases only from No. 1 to No. 3 voussoir, then continues the same to the last voussoir, No. 9. There is this accordance in the two curves, namely, that lateral forces measured on the base line (*a c*), or the average distance from the extrados to the intrados, equal half the span of the arch, which is the radius of the same circle.

Of the Hyperbolic Arch. — The curve of this arch so nearly resembles that of the parabola, as to require a similarly formed extrados, having this difference, that the base *h a* (fig. 6) must equal *a l*, having *h g* parallel with the hyperbola as high as *f*. Arches being rarely, if ever, built after the manner of this curve, it will be useless to go any farther into its qualities.

Of the Cycloidal Arch. — In the diagram (fig. 7) are drawn three curves. First, the dotted curve, which is the cycloid; second, the semicircular arch (*a b c d e*) passing through the three points *b c*, and *d* of the cycloid, and having its centre at *i*; and the third is also a semicircular arch (*f g c h*), having its centre at *k*, which coincides with the cycloid almost to the two points *b* and *d*; but near these

points the cycloid partakes more of the ellipse, by falling within the circular curve from *g* to *b*. It may be safely in-

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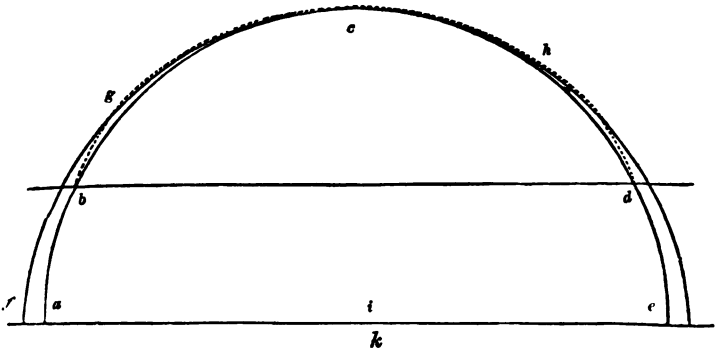

ferred, from these circumstances, that an arch constructed of masonry, of the cycloidal form, would require its extrados, from *c* to *g*, to be equal to the extrados of the large semicircle, *f*, *g*, *c*, *h*.

Of the Catenarian Arch.—In consequence of the close similarity between the catenarian curve and the parabolic, there cannot exist a doubt but that, in all structures, the same extrados will effectually answer for both.

During the consideration of the extrados to the circular and other curves, the effects of friction were not allowed for, since the voussoirs, throughout the experiments, were suspended in the air by the two lines, the perpendicular and the horizontal, with the balancing weights attached to each. The only friction which can be named arose from the axes of the pulleys and the bending of the lines.

ESSAY II.

EXPERIMENTS, WITH WEIGHTS AND STRUCTURES, ON ARCHES OF VARIOUS DIMENSIONS, COMPOSED OF WOODEN VOUSSOIRS, AND OF BRICKS, WITHOUT CEMENT, BUT HAVING THE AID OF FRICTION, AND IMMOVABLE BUTTRESSES AT THE BASE, OR FOUNDATION.

EXPERIMENT *First.* — The scale proposed to be adopted for the diagram (fig. 8) is an eighth of an inch to an inch. The semicircular arch (*a*, *b*, *c*) is 24 in. in span, and composed of twenty wooden voussoirs; the dimensions of each

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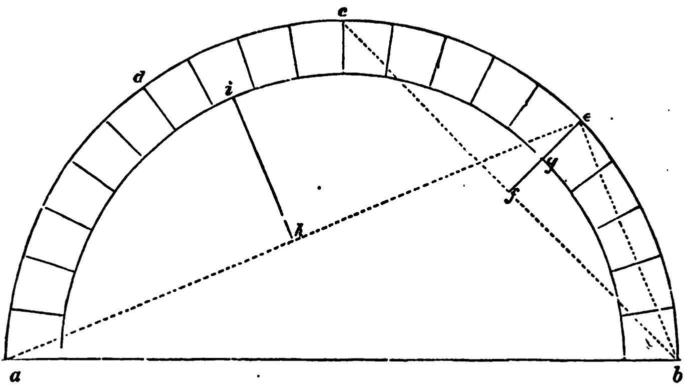

of which are 4 in. long, 2½ in. wide, and 2 in. in average thickness; the weight of each is half a pound, so that the whole arch weighs ten pounds. Having placed this arch on a table, and secured the voussoirs *a* and *b* from being pressed out, a pound weight was put on the crown at *c*, which the arch supported; but, a quarter of a pound more being added, it gave way by sinking at c, and flying out at the points d

and e, or between the fifth and sixth voussoirs from the foot and crown.

The dotted line b c is drawn straight from the crown of the arch (c) to the outside of the lowest voussoir (b); and the line f g, which is drawn perpendicular to b c, denotes the farthest point, f, from the intrados at g, and which is, in this instance, $1\frac{3}{4}$ in.

Experiment Second. — The same arch (fig. 8), at the point e, carried 4 lb., but it gave way when half a pound more was added. The dotted line e b lies within the voussoirs; but the dotted line a e, at the point h, equals $6\frac{1}{2}$ in. from the intrados of this arch at i.

Experiment Third. — The arch (a b c) (fig. 9) is composed of fifteen voussoirs, and is $22\frac{1}{4}$ in. in span, being a

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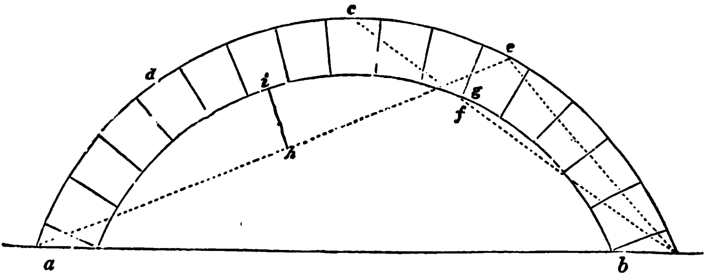

segment of the semicircular arch (fig. 8). This segmental arch sustained on the crown, at c, a weight of 42 lb.; but it gave way with a weight of 56 lb, by sinking down at c, and by being forced out at the points d and e; the voussoirs at a b were secured from being pressed outwards. The dotted line c b almost touches the intrados at g.

Experiment Fourth. — The same arch of fifteen voussoirs (fig. 9) sustained, at the point e, $3\frac{1}{2}$ lb, but gave way when half a pound more was added. The perpendicular h i equals $3\frac{1}{2}$ in.

Experiment Fifth. — The arch (a b c) (fig. 10) is com-

posed of twelve voussoirs, out of the twenty voussoirs of the semicircular arch (fig. 8), and is rather more than 19 in. in span. On the voussoirs at *a b* being made immovable, I placed my foot on the crown at *c*, and stood with my whole weight upon it (a weight equalling 147 lb), and it sup-

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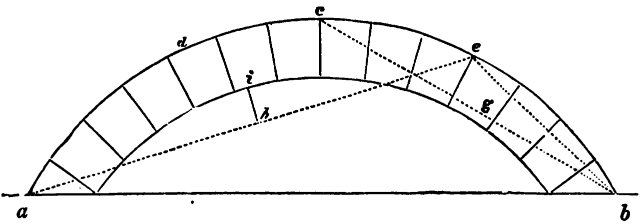
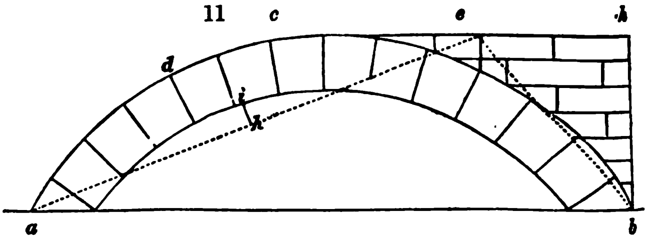


ported me without yielding in the least degree. The dotted line *c b* lies in this arch, quite within all the voussoirs. The line of the joint of the voussoirs, at *e*, is nearly at right angles to the line of force (*c b*); therefore, the weight has no tendency to displace or force those voussoirs upwards.

Experiment Sixth.—As this arch proved to be so very strong, I determined upon finding out its weakest parts; and, by trying different weights, I discovered them to be at the points *d* and *e*, just half way between the crown (*c*) and and base (*a b*). When the weight of 6 lb. was placed at *e*, the arch was balanced with it; but, on attempting to add more, the arch sank at *e*, and was forced out at *d*. The straight line *h i* equals 1¾ in.

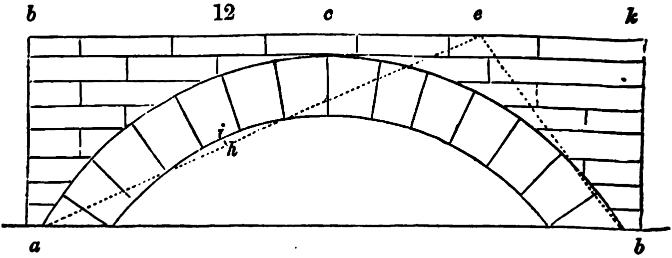
Experiment Seventh.—Fig. 11 is the same segment of an arch as fig. 10, being composed of twelve voussoirs. Between *c* and *b* some wooden bricks were placed, as represented by *c k b*, which were built up regularly. At the point *e*, which is perpendicularly over the weakest part of the arch on this side, some weights were placed, and the arch was found just to balance with 14 lb.: the brickwork

consisted of fifteen wooden bricks, eight of which weighed 1 lb. The dotted line *e b*, in the diagram, is almost without



the voussoirs; and the dotted line *a e*, at the point *h*, is about 1 in. from the intrados at *i*.

Experiment Eighth. — When both sides of the arch were bricked up as represented in fig. 12, and one course of brickwork over the crown at *c*, this arch, of twelve voussoirs, just balanced with 21 lb, placed, as before, at *e*. The



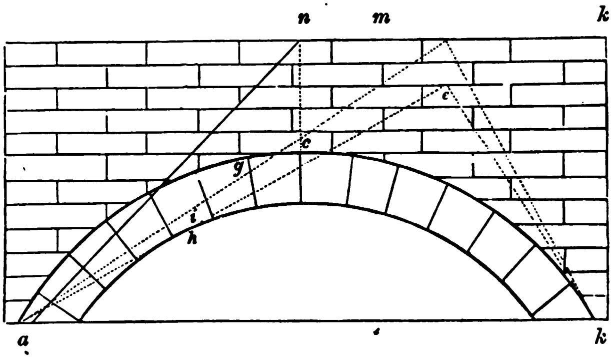
number of wooden bricks on each side of the arch was fifteen, and four on the top, making, in all, thirty-four, eight of which weighed 1 lb. The dotted line *a e*, at *h*, is only $\frac{3}{4}$ in. from the intrados at *i*.

Experiment Ninth.—The diagram (fig. 13) had the brickwork raised three courses above the crown of the arch (*a b c*), which arch was also composed of twelve voussoirs. At the point *e*, 56 lb were placed, which the arch firmly sustained; and, on raising the fabric two more courses, the arch, at the point *m*, carried my weight, or a weight of

147 lb. The dotted line *e a*, in the first case, just touches the intrados at *h*, so that the straight line *h i* vanishes. In the second instance, the dotted line *a g m* lies considerably within the voussoirs, similar to the dotted line *c g b*, in the fifth experiment.

Let a weight be placed at *n*, which is perpendicularly over *c*; then the straight line *n a* is the shortest, and most

13

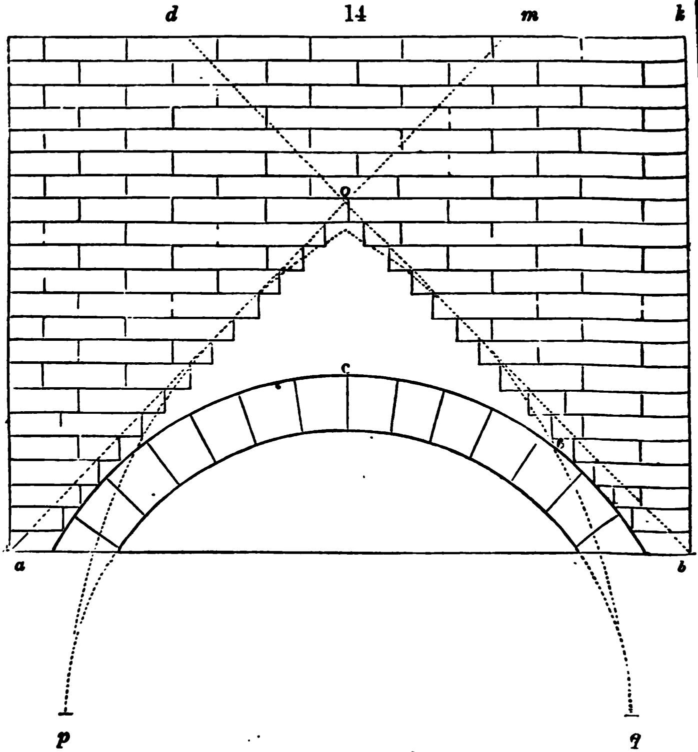


direct one from the weight itself, or from where it is placed, to the ground at *a*, by which it is ultimately supported. For, if it be not, let the force act from *n* to *c*, and from *c* to *a*; and we have then, in the figure *n c a*, a triangle, having the two sides, *n c*, and *c a*, less than the third side (*n a*), which is impossible; therefore the straight line *a n* is the shortest direction of the force. For the same reason, the dotted lines *m a*, *e a*, *m b*, and *e b*, are the most direct lines by which the force of any weight, placed at *m*, or *e*, acts on the ground at the points *a* and *b*.

Experiment Tenth.— Having raised the brickwork above the arch (*a c b*) (fig. 14), so that the dotted line *a m*, and the line *a b*, contained an angle (*m a b*) equal to 45°, the point *m* being perpendicularly over *e*, the arch was taken away, as also the brickwork between the crown c, and where

the dotted lines *a m*, *b d*, cut each other at *o*. The fabric thus left standing, was supported on the piers *a b* by the natural arch, formed by the projection of a brick in each course over the opening, until the projecting bricks met at *o*.

This goes to verify the old adage, that, the more an arch is loaded by regular masonry, the more it will bear; but



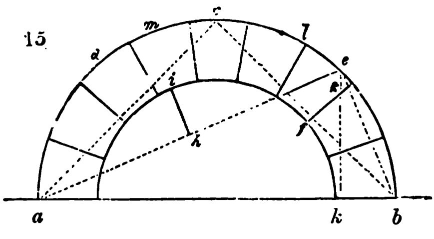
the truth is, as may be seen by this experiment, that the more it is loaded, the less it has to bear, since the maximum of the weight is limited at the intersection of the two dotted lines *a m* and *b d*; because the structure above these lines is then borne by the piers (*a*, *b*) of the natural arch

($a\ o\ b$). The arch, therefore, in this instance, becomes a centering only, on which the superstructure is erected. Whenever, then, a centering of this kind is required, on which to erect a high wall or building, as a tower, the Gothic form of an arch is the best, since it is of a form which coincides the nearest to the natural arch (for any breach through a wall of masonry takes this form in the upper part of the opening); at the same time, it possesses a great degree of beauty and elegance.

From what has been before shown, the fabric without the arch will bear at the point m, which is perpendicularly over e, any weight, since the dotted line $m\ a$ passes within the masonry; and, consequently, it will sustain any weight on any other part of the masonry, if the piers at a and b are kept in their places.

Experiment Eleventh. — The semicircular arch ($a\ b\ c$) (fig. 15) is of 10 in. span, and is composed of nine wooden voussoirs. The dimensions of the voussoirs are the same as

15



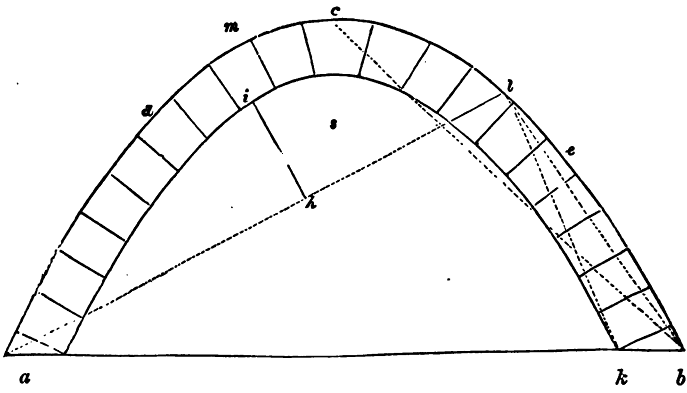
those used in the ten preceding experiments, and their average thickness is $2\frac{1}{2}$ in.; the weight of the whole arch is $4\frac{1}{2}$ lb.

Having placed this arch on a table, and secured the bottom voussoirs at a and b, it then carried my weight as firmly as possible, when standing on one foot on the crown, at c. In this experiment the dotted line $c\ b$ lies quite within the voussoirs; and the distance from f to g in the intrados is half an inch. The point h, in the dotted line $a\ e$, is 2 in. distant from the point i, in the intrados.

The arch, at the point *e*, carried my weight, because a perpendicular line (*e k*) could be drawn within the voussoirs to *b*; therefore there was no lateral force sufficient to overturn the voussoirs between *e* and *a*, it being counteracted by the friction between the surfaces of the two bottom voussoirs (*e* and *b*). But, when a weight was placed at *l*, the arch balanced with 28 lb; consequently, *l* is the weakest part of the arch, with voussoirs of this proportion of depth.

Experiment Twelfth. — The arch (fig. 16) carried on the crown, at *c*, 50 lb; but, when 6 lb more were added, it opened at *d* and *e*, and fell down. The arch is 24 in. in span, and the dimensions of the voussoirs are the same, as to

16



weight, as in the preceding experiments. The arch carried 3 lb. at the point *l*, but gave way with 4 lb., by being forced out at *m*. The dotted lines *a*, *l*, at *h*, is 4½ in. from the intrados at *i*.

Experiment Thirteenth, on Pointed Gothic Arches.—The arch (*a e b*) (fig. 17) is of 24 in. span, and composed of the same voussoirs as used in the preceding experiments, with the addition of a few wooden bricks, introduced between

the voussoirs to increase the dimensions of the circle. When this arch was placed on a table, it required a 2-lb weight at *c* to balance the upward pressure of the sides, and to preserve it from falling, in consequence of the shallowness of the voussoirs at *o p*, in this diagram. When 1 lb more was added to the two, the arch carried it well

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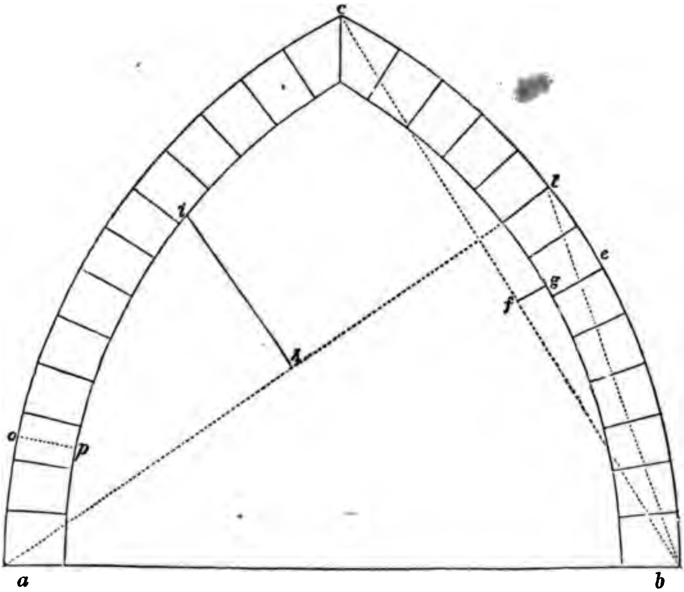

but, under the total weight of 4 lb, the arch gave way, by the crown sinking, and by the sides being forced out. The straight line *f g* equals 1½ in. At the point *l*, this arch would only carry 1 lb.; and the straight line *h i* equals 7 in. from the intrados at *i*.

Experiment Fourteenth. — The small Gothic arch *a b c* (fig. 18) is of 12 in. span; and it carried, on the crown, at *c*, 14 lb. In this instance the straight line *f g* nearly vanishes. At the point *l*, the arch carried 5 lb; but it was

forced out at *d*, on the addition of another pound. The line *h i* equals $2\frac{1}{2}$ in. in length.

Having submitted to experiment with weights the several preceding arches, it would now be well to take into consideration the effects consequent on the variations of the straight lines *f g* and *h i*, as derived from the dotted lines *a c*, *c b*, *a e*, and *a l*, in the different preceding figures.

Facts have shown, that, in proportion to the length of the straight lines *f g* and *h i*, so has the power of the arches decreased, or they are inversely to each other; meaning, that

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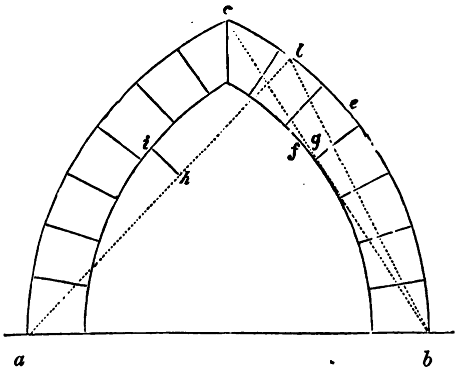


the greater the curvature between the two points *a c*, *c b*, *a e*, or *a l*, or the less the depth of the voussoirs *o p*, the less is the strength of the arch. Again, the arches have always given way, and the voussoirs have been forced outwards, at the midway point between the extremes *a* and *c*, *a* and *e*, and *a* and *l*. When, however, the same dotted lines have fallen at a distance within the voussoirs, as instanced in the experiments fifth, ninth, and eleventh, the arch, or arches, have borne almost any weight. The same result has taken place when the shallowness of the voussoirs required the aid of a superstructure of wooden

bricks to cause the dotted lines to fall within the voussoirs, or above the intrados.

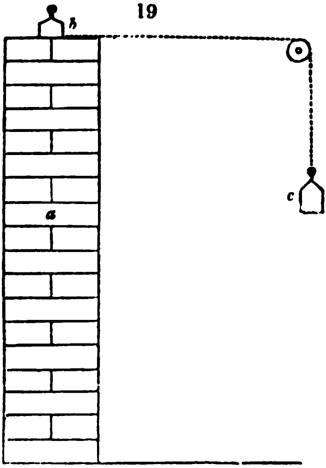
The conclusion which may be fairly drawn from these experiments and remarks is, that weight acts in straight lines, and always takes the nearest or most direct course from itself, or from where it is placed, to the ground by which it is ultimately supported, as in the ninth experiment (fig. 13). This being the case, the two extremes of the curvature of every segment of an arch (as *a c*) (fig. 8), act as levers, having as the fulcrum the centre point of the intrados, which is opposite to *d* between the extremes; and which, therefore, is measured by a line (as *i h*, or *g f*) drawn from the centre of motion; or the fulcrum *i g*, perpendicular to the direction of the line of force, or weight, as at *a c*, &c. (See *Wood's Mechanics*, articles 81, 82, and 83).

This force is increased as *i h*, or *f g*, lengthens; and is in proportion to the approximation of the two extreme points *a* and *c*, &c.; consequently, when an arch once begins to give way, its destruction becomes inevitable, being expedited and made certain by the continued increasing length and power of these two levers (like the handles of a pair of pincers or nut-crackers), of half the arch, or of the four levers, when the whole arch is considered.

ESSAY III.

OF THE LAWS RELATIVE TO PIERS AND BUTTRESSES.

19



Firstly. — The diagram fig. 19, drawn to the scale of one eighth of an inch to an inch, represents a pier (*a*), which is composed of wooden bricks, eight of which weigh 1 lb. This pier has a weight (*b*) on the top; and a string, pulley and weight (*c*) at the end, to measure the lateral or horizontal force up to the balancing point. The following are the results of the first experiment: —

Height of the pier.	Dimensions of of the pier.	Weight of the pier.	Weight on the top of the pier.	Balancing lateral force.	The proportion of the lateral force to the weight of the pier, and the weight placed on the top of it.
18 in.	4 in. by 4 in.	$4\frac{1}{2}$ lb.	1 lb.	$\frac{1}{4}$ lb.	$\frac{1}{22}$ part.
18	4 ... 4	$4\frac{1}{2}$	2	$\frac{5}{16}$	$\frac{1}{21}$
18	4 ... 4	$4\frac{1}{2}$	4	$\frac{3}{8}$	$\frac{1}{22}$
18	4 ... 4	$4\frac{1}{2}$	8	$\frac{7}{16}$	$\frac{1}{28}$

On reducing the height of the pier three courses of bricks at a time, and with a weight of only 1 lb placed on the top of it, the results of the lateral forces were as follows: —

Height of the pier.	Dimensions of the pier.	Weight of the pier.	Weight on the top of the pier.	Balancing lateral force.	The proportion of the lateral force to the weight of the pier, and the weight placed on the top of it.
15 in.	4 in. by 4 in.	$3\frac{3}{4}$ lb.	1 lb.	$\frac{5}{16}$ lb.	$\frac{1}{15}$ part.
12	4 ... 4	3	1	$\frac{3}{8}$	$\frac{1}{11}$
9	4 ... 4	$2\frac{1}{4}$	1	$\frac{1}{2}$	$\frac{1}{6}$
6	4 ... 4	$1\frac{1}{2}$	1	$\frac{7}{16}$	$\frac{1}{4}$

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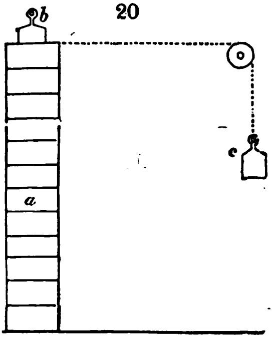

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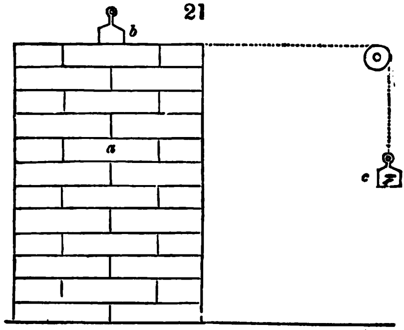


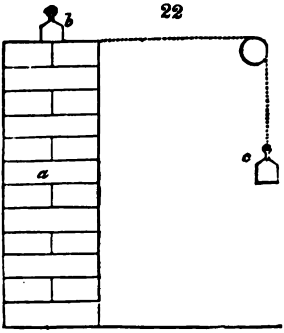
The pier *a*, fig. 20, is 2 in. in thickness, 12 in. high, and it was increased in length from 6 in. to 12. The lateral force was applied at right angles to the length; and the following are the results:—

Height of the pier.	Dimensions of the pier.	Weight of the pier.	Weight on the top of the pier.	Balancing lateral force.	The proportions of the lateral force to the weight of the pier, &c.
12 in.	2 in. by 6 in.	$2\frac{1}{4}$ lb.	1 lb.	$\frac{1}{8}$ lb.	$\frac{1}{26}$ part.
12	2 ... 8	3	1	$\frac{1}{8}$	$\frac{1}{32}$
12	2 ... 10	$3\frac{3}{4}$	1	$\frac{1}{8}$	$\frac{1}{38}$
12	2 ... 12	$3\frac{1}{2}$—$4\frac{1}{2}$	1	$\frac{3}{16}$	$\frac{1}{29}$

The pier *a*, fig. 21, is 2 in. in thickness; the length increases from 4 in. to 8 in., the height continuing the same as in the last figure; but the lateral force is applied in the direction of the length, and the results are as follow:—

Height of the pier.	Dimensions of the pier.	Weight of the pier.	Weight on the top of the pier.	Balancing lateral force.	The proportion of the lateral force to the weight of the pier, &c.
12 in.	4 in. by 2 in.	$1\frac{1}{2}$ lb.	1 lb.	$\frac{5}{16}$ lb.	$\frac{1}{8}$ part.
12	6 ... 2	$2\frac{1}{4}$	1	$\frac{9}{16}$	$\frac{1}{6}$ nearly
12	8 ... 2	3	1	$1\frac{1}{16}$	$\frac{1}{4}$

22



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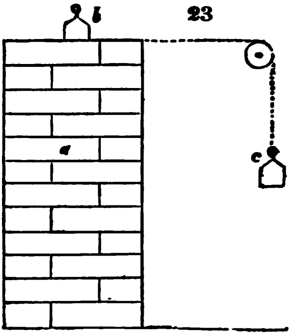

The piers, figs. 22, 23, and 24, are of equal height, and contain the same quantity of materials; because the re-

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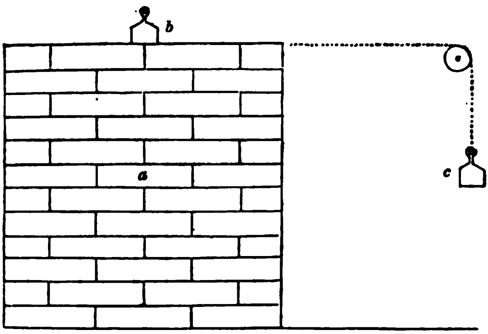


spective dimensions of each, when multiplied into each other, give the same result. The lateral force, however, is applied differently to each; the base of the pier *a*, fig. 22, being 4 in. to oppose the force; that of *a*, fig. 23, being

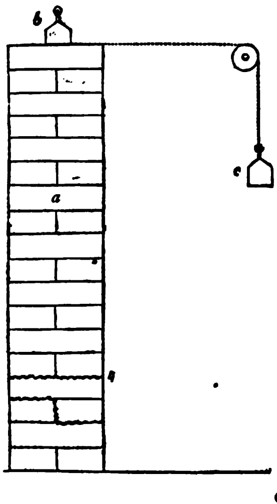
6 in.; and that of *a*, fig. 24, being 12 in. The results are as follow: —

Height of the different piers.	Dimensions of the piers.	Weight of the piers.	Weight on the top of the piers.	Balancing lateral force.	The proportions of the lateral force to the weight of the pier, &c.
Fig. 22 12 in.	4 in. by 6 in.	$4\frac{1}{2}$ lb.	4 lb.	$1\frac{1}{3}$ lb.	$\frac{1}{7}$
Fig. 23 12	6 ... 4	$4\frac{1}{2}$	4	1	$\frac{1}{6}$
Fig. 24 12	12 ... 2	$4\frac{1}{2}$	4	3	$\frac{1}{3}$

Piers with square bases, of the same height as the last three figures, but of different dimensions, have the following results: —

Height of the piers.	Dimensions of the piers.	Weight of the piers.	Weight on the top of the piers.	Balancing lateral force.	The proportion of the lateral force to the weight of the piers, &c.
12 in.	4 in. by 4 in.	3 lb.	4 lb.	$\frac{7}{8}$ lb.	$\frac{1}{8}$ part.
12	6 ... 6	$6\frac{3}{4}$	4	$1\frac{3}{4}$	$\frac{1}{6}$
12	6 ... 6	$6\frac{3}{4}$	8	$2\frac{5}{8}$	$\frac{1}{6}$
12	8 ... 8	12	8	$4\frac{1}{8}$	$\frac{1}{5}$

25



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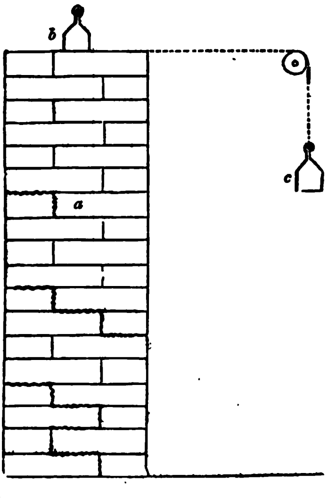


The piers *a a*, figs. 25 and 26, are both 18 in. in height, with bases of 4 in. by 4 in., and 6 in. by 4 in., respectively. They are introduced to show where the lateral force breaks, or causes the piers to open, under different weights placed on their top. The following are the results of the experiments: — First, on fig. 25.

Height of the pier.	Dimensions of the pier.	Weight of the pier.	Weight on the top of the pier.	Overturning lateral force.	Number of courses above the base where the pier opens before falling.
18 in.	4 in. by 4 in.	$4\frac{1}{2}$ lb.	$\frac{1}{4}$ lb.	$\frac{1}{4}$ lb.	3 courses above the base.
18	4 ... 4	$4\frac{1}{2}$	1.	$\frac{5}{16}$	$2\frac{1}{2}$
18	4 ... 4	$4\frac{1}{2}$	2	$\frac{5}{16}$	$2\frac{1}{2}$
18	4 ... 4	$4\frac{1}{2}$	4	$\frac{7}{16}$	$2\frac{1}{2}$
18	4 ... 4	$4\frac{1}{2}$	8	$\frac{1}{2}$	$2\frac{1}{2}$

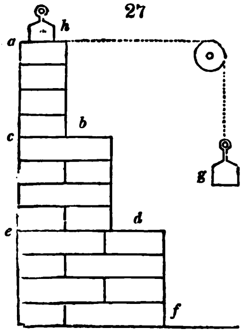
Result of Experiments with fig. 26.

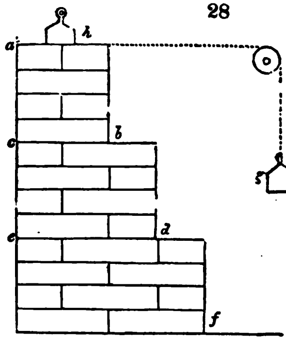
Height of the pier.	Dimensions of of the pier.	Weight of the pier.	Weight on the top of the pier.	Overturning lateral force.	Number of courses above the base where the pier opens before falling.
18 in.	6 in. by 4 in.	$6\frac{3}{4}$ lb.	$\frac{1}{2}$ lb.	$\frac{11}{16}$ lb.	12th and 8th courses.
18	6 ... 4	$6\frac{3}{4}$	1	$\frac{11}{16}$	12th on $2\frac{1}{2}$ courses.
18	6 ... 4	$6\frac{3}{4}$	2	$\frac{13}{16}$	12th on $2\frac{1}{2}$ courses.
18	6 ... 4	$6\frac{3}{4}$	4	$1\frac{1}{8}$	4 courses, and diagonally to base.
18	6 ... 4	$6\frac{3}{4}$	8	$1\frac{1}{2}$	4 courses, and diagonally to base.

Secondly, of Buttresses.— The bricks are the same as in the seven preceding figures, and the diagrams are on the same scale.

Let figs. 27 and 28 be two buttresses, and the following are their dimensions, and the results of the lateral force acting upon them.

It will be observed, that the results of the experiments on both figs. 27 and 28 are the same.





Relative to fig. 27.

Piers composing buttresses.	Height of piers.	Dimensions of the piers.	Total height of the buttresses.	Weight of the piers.	Total weight of the buttresses.	Weight on the top of the buttresses.	Results and observations.
a b	4 in.	2 in. by 4 in.	12 in.	½ lb.	3 lb.	2 lb.	Lateral force causes the buttresses to give way on *c b.*
c d	4	4 ... 4	12	1	3	4	Ditto on the base *c b.*
e f	4	6 ... 4	12	1½	3	8	Ditto on the base *c b.*

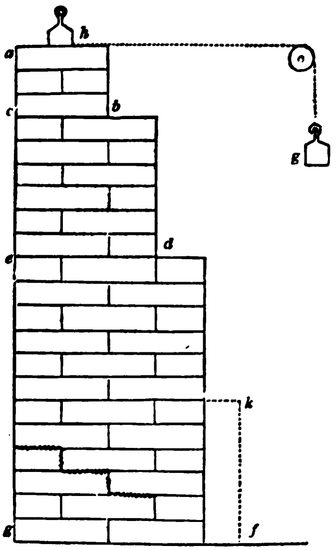
Relative to fig. 28.

Piers composing buttresses.	Height of piers.	Dimensions of the piers.	Total height of the buttresses.	Weight of the piers.	Total weight of the buttresses.	Weight on the top of the buttresses.	Results and observations.
a b	4 in.	4 in. by 4 in.	12 in.	1 lb.	4½ lb.	2 lb.	Lateral force causes the buttress to give way on *c b.*
c d	4	6 ... 4	12	1½	4½	4	Ditto on the base *c b.*
e f	4	8 ... 4	12	2	4½	8	Ditto on the base *c b.*

The buttresses (figs. 27 and 28), by their yielding to the lateral force at their respective bases (*c b* and *c b*), proved the lower structures of each to be of unnecessary stoutness, in proportion to the upper parts, *a b* and *a b*. A buttress erected for the purpose of supporting and resisting a lateral force at *a* should give way only at the base line *f f*. (See the piers, figs. 25 and 26.)

With the view of determining the true proportions of such a buttress, a pier was constructed, having its base 8 in. by 4 in., and raised to the height of 12 in., or twelve courses. This pier was submitted to the test of the lateral force, and yielded under the weight of 2½ lb: a 4 lb weight was previously placed on the top, and in the centre of the pier; a 1 lb and a 2 lb weight having been found too light to prevent the top courses from slipping off under the lateral force. The pier gave way at the base, and diagonally towards it.

29



Another pier was next constructed, measuring 6 in. by 4 in. at the base, and raised indefinitely to the height of eight or ten courses, or inches, and a 4 lb weight placed on the top. This pier being also submitted to the lateral force, as in the previous experiment, required the courses to be taken down to the sixth from the base before it would just balance, as the first had done, under the 2½ lb lateral force.

A third pier was then built up, having a base 4 in. by

4 in.; and, when raised three courses in height, with the 4 lb weight on the top, it also just balanced against the lateral force of $2\frac{1}{2}$ lb, the same as the two former piers.

These three piers were placed one upon the other, as represented in the diagram fig. 29, by *e f*, *c d*, and *a b*, with the 4 lb weight on the top. When this compound pier, or buttress, was submitted to the test of the lateral force applied at *a*, the whole, or the buttress, balanced against $2\frac{1}{16}$ lb, giving way diagonally on the base line *f g*, as was required of a true proportioned buttress.

Particulars relative to the Buttress fig. 29.

Piers composing the buttress.	Dimensions of the piers.	Height of the piers.	Total height of the buttress.	Weight of the piers.	Total weight of the buttress.	Weight on the top of the buttress.	Results and observations.
a b	4 in. by 4 in.	3 in.	21 in.	$\frac{3}{4}$ lb.	9 lb.	4 lb.	The lateral force caused the buttress to give way on the base line *g f*, breaking diagonally from the fourth course to the base.
c d	6 ... 4	6	21	$2\frac{1}{4}$	9	4	
e f	8 ... 4	12	21	6	9	4	

The total weight of the buttress fig. 29, including the weight on the top, equalled 13 lb; and the lateral overturning force equalled $2\frac{1}{16}$ lb, or one sixth the weight of the buttress and the weight placed on the top of it. The increased height, or length of lever, formed by one pier being placed upon another, and these two upon a third, was considerably counteracted by their respective weights acting towards the same outside, instead of being in the middle: but more of this presently.

On the top of the buttress fig. 29 a 2 lb weight was substituted for the 4 lb weight; and then the whole was submitted to the lateral force of $2\frac{1}{2}$ lb. The result was, that the buttress gave way on the top of the pier *e f*; thus

proving the 2 lb weight too light. Under the 4 lb weight the buttress first gave way on the base *g f*, and next

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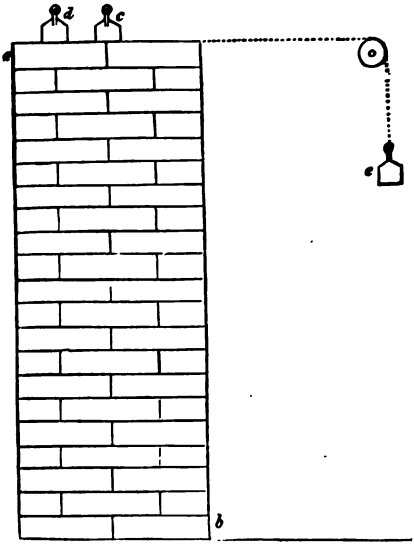


on the base *e d*, in consequence of the inclination which caused the centre of gravity of the piers above to act, or fall without the base *e d*. A 7 lb weight being put on the top, in the place of the 4 lb weight, did not alter the breaking of the buttress towards the bottom, which was much the same as under the 4 lb weight, perhaps half a course lower; thus proving that a greater weight acts more favourably than otherwise, though a greater weight than 4 lb was not actually necessary in this instance. The proportions of the dimensions of this buttress require notice; since the height decreases in geometrical progression, and the several dimensions in arithmetical progression.

The diagram fig. 30 is to show the difference of the effects of the same weight being placed on the top, in the middle, or towards the farther side from the lateral force.

This pier is of the same height as the buttress fig. 29, and of equal dimensions at the base. The following are the results: —

Pier.	Dimensions of the pier.	Height of the pier.	Weight of the pier.	Weight on the top of the pier.	Balancing lateral force.	Conditions.
a b	8 in. by 4 in.	21 in.	$10\frac{1}{2}$ lb.	4 lb.	$1\frac{5}{8}$ lb.	With the weight in the middle at *c*.
a b	8 ... 4	21	$10\frac{1}{2}$	4	$2\frac{1}{16}$	Ditto at the outside at *d*.

The buttress fig. 29 and the pier fig. 30 agree precisely, as it regards requiring the same lateral force, when the weight on the pier is placed at *d*; thus proving that a buttress of the construction of fig. 29 is as strong as this pier fig. 30, which is composed of less materials by $1\frac{1}{2}$ lb in weight, or in the proportion of nearly one tenth part.

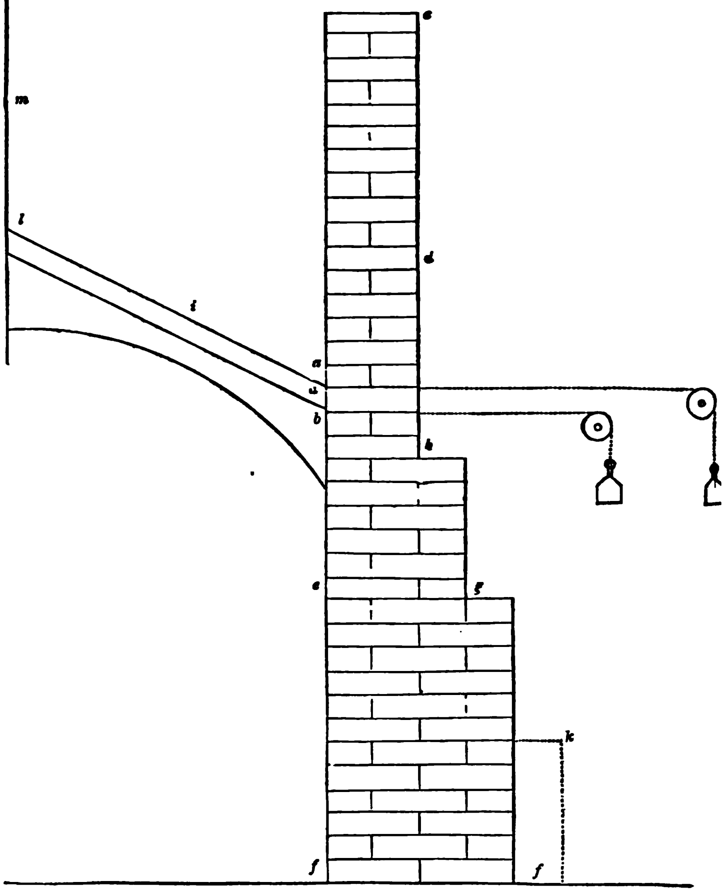
To return to the buttress fig. 29: since this buttress appears to answer the purpose intended, it will not be amiss to delineate its parts more fully, by introducing another diagram, in which bricks will be substituted for the 4 lb weight on the top, and thus complete the buttress. A few observations will necessarily follow: —

Fig. 31 represents the buttress fig. 29 completed; in which *a* is the point of resistance, as in fig. 29; *a c* is the balancing height on *f f*, and is equal in weight to 4 lb When *b* is made the point of resistance to a lateral force, then *b d* is the balancing height on *e g* only; and *a h* : *a c* :: 1 : 6, *b h* : *b d* :: 1 : 3. The proper situation for the spring of a flying buttress (*i l*, against the wall *m*) is at the points *a* and *b*, being the parts of the buttress which offer the greatest resistance to a lateral force.

Experiments to ascertain the Laws relative to the Pressure of the perpendicular loose Soil of any Bank, against Walls of Masonry of different Dimensions.— The materials made use of in this instance were peas, which were placed in a

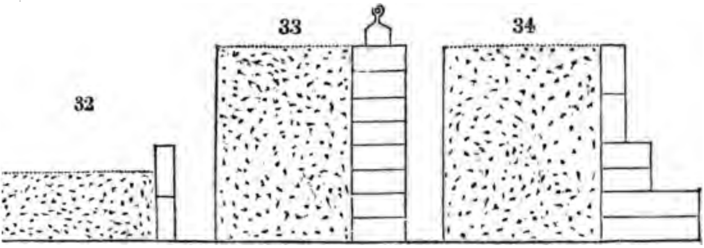
cubical box measuring 8 in., and leaving one side movable for the wall. The weight of the peas equalled 15 lb.

31



Experiment First. (fig. 32.)—A wall, one inch in thickness, and composed of eight wooden bricks, was erected, the dimensions of each of which were 2 in. wide by 4 in.

long, and 1 in. thick; the eight bricks weighed 1 lb. On constructing this wall, it gave way when it was raised



4 in. in height; the peas within the box being 3 in. high. When the wall was raised up 2 in. higher, having the peas in the box also raised $\frac{2}{3}$ in. higher, the wall required a 2 lb weight to be placed on its top, which just balanced the pressure of the peas. On completing the wall to 8 in. in height, and the peas being filled up level with the rim of the box, the wall just balanced with 6 lb on the top; a positive proof of the wall itself being insufficient to sustain the internal pressure.

Experiment Second. (fig. 33.)—In this case the wall was made 2 in. thick, and composed of sixteen bricks; the wall being 8 in. high, and its weight equalling 2 lb. The peas within were level with the top of the box; and their weight, as before stated, equalled 15 lb. This height and weight of peas caused the above wall to give way; but, on putting a 1 lb weight on the top, it just balanced against the pressure of the peas.

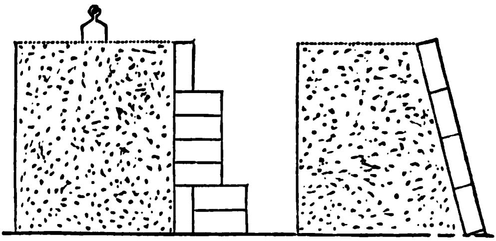
From these two experiments it appears, that, by doubling the thickness of a wall, less than half the weight is sufficient to maintain the outward pressure of the bank within.

Experiment Third. (fig. 34.)—This wall consisted of sixteen bricks, and just balanced against the pressure of the full box of peas.

Experiment Fourth. (fig. 35.)—This wall consisted of sixteen bricks, carried a 4 lb weight, placed in the centre

on the surface of the peas. When this last wall was reversed, or placed with its projections inside among the peas, it only just balanced with the pressure of the peas against it; thus proving the greater strength to be when the set-offs are placed on the outside, or in the buttress manner.

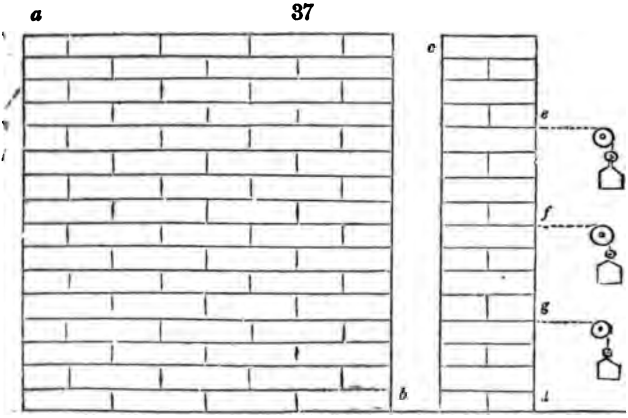
35 36



Experiment Fifth. (fig. 36.)—When a wall 1 in. thick, and composed of eight bricks, was inclined 15° from the perpendicular towards the peas, it just balanced against their weight.

Experiment Sixth.—When the same wall was inclined 23°,

37



it balanced with 2 lb placed on the peas in the centre. The angle at which the peas stood naturally inclined was 36°.

On the Strength of Walls against lateral Force.—The following diagrams are upon the same scale as the preceding figures, and constructed of wooden bricks. The letters *a b*, in figs. 37 and 38 respectively, represent the front elevation; and *c d*, in both figures, the side view, or section, of the walls. The following are the results relating to fig. 37:—

Wall.	Dimensions.	Height.	Weight.	Points where the lateral force was applied.	Lateral force.
a b	16 in. by 4 in.	16 in.	16 lb.	At *e*	$1\frac{11}{16}$ lb.
a b	16 ... 4	16	16	*f*	$2\frac{7}{8}$
a b	16 ... 4	16	16	*g*	6

Under the first experiment, at the point *e*, the wall gave way, diagonally, from the eighth to the fourth course from the bottom, opening at both places opposite to the force. Under the second and third experiments, at the points *f* and *g*, the wall gave way on the bottom course.

The following are the particulars relating to fig. 38:—

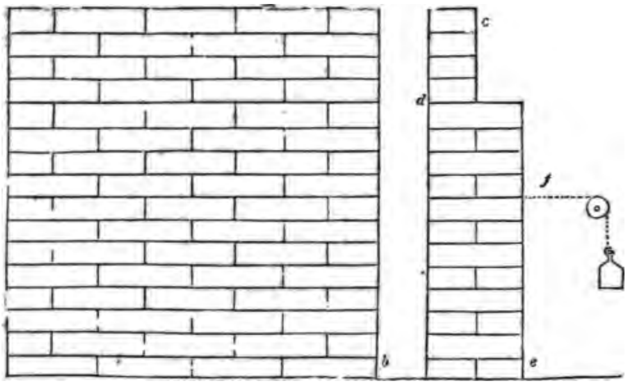
Wall.	Dimensions.	Height.	Weight.	Lateral force applied.	Lateral force.
e d	16 in. by 4 in.	12 in.	12 lb.	At *f*, or 8	$2\frac{7}{8}$ lb.
d c	16 ... 2	4	2	courses up.	$2\frac{7}{8}$

It appears from the above table, on comparing the lateral force with that in the table relating to fig. 37, that, when the force is applied at the same height from the base, the resistance is equal in both instances, although the four top courses in fig. 38 have been reduced to half the weight of the same number in fig. 37. This has been before shown to be the case on lightening the weight on the top of structures of this kind, as explained by the table relating to fig. 19.

On farther reducing this wall in thickness four courses lower, or, altogether, eight courses, and applying the lateral force at the eighth course, as shown by the diagram fig. 39, the lateral force required to overturn this wall was $2\frac{5}{8}$ lb; but, when the wall was still farther reduced in thickness to

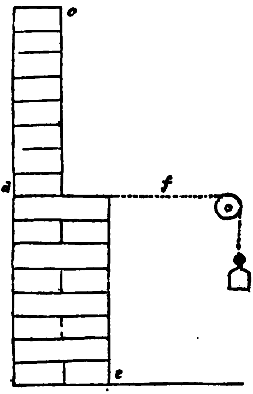
within four courses of the base, as shown by fig. 40, the lateral force required to overturn it was only 1 lb. In the

a 38



former of these two experiments (figs. 39 and 40), the wall gave way on the bottom course; and, in the latter, the wall broke on the base *d*, the force being applied at *f*. On constructing the same wall, as represented in the end view

39



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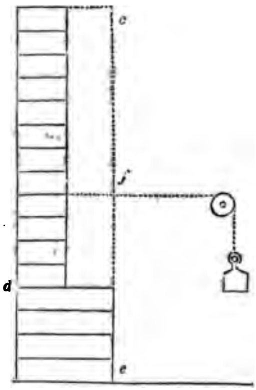
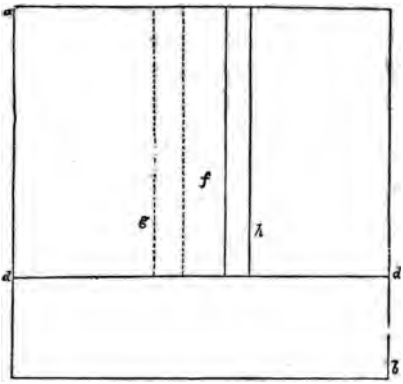


of fig. 40, but adding to it a pilaster of 2 in. in width, placed on the base *d*, as shown by the dotted line in that

diagram, the result was, that, when applying the lateral force at *f*, it required $2\frac{1}{8}$ lb to balance it.

By increasing the pilaster to 4 in. in width, as shown by *g h*, fig. 41, and applying the force at *f*, as before, $2\frac{1}{2}$ lb were necessary to balance the wall.

41



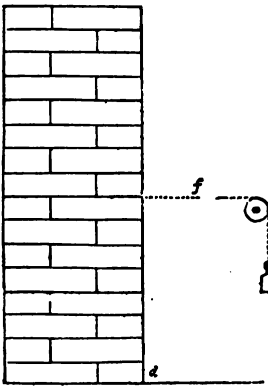
From these two experiments it appears that pilasters, or flat buttresses, are of service in giving strength to a thin wall; but the plan will only answer where the force, as of the wind, can act on one side. The cause of the increased strength given to a wall by a pilaster is owing, in a great measure, to the centre of gravity of such wall being the farthest within the base, and having the base of the pilaster of the same depth (as in fig. 37); but, it must be observed, that the lateral force is applied directly through the pilaster, and the force, as of the wind, would act on the whole length of the wall; therefore, in order to obtain the true value of the pilasters, the average lateral force must be taken between walls without pilasters, and walls with them; which, in the above case, is $1\frac{3}{4}$ lb, being the average between 1 lb and $2\frac{1}{2}$ lb.

The quantity of material composing the wall fig. 41 is

about a quarter less than that of fig. 37; and the difference in strength of the former to the latter is not quite half; the lateral resistance of fig. 37 being $2\frac{7}{8}$ lb, and that of fig. 41 being $1\frac{3}{4}$ lb; which makes a difference of $1\frac{1}{8}$ lb in favour of fig. 37. Now, in fig. 38 the material saved is one eighth of that in fig. 37, with very little loss of strength.

A hollow wall was next erected, being constructed on the same scale, as to length and height, as the five preceding figures, but of two additional inches in thickness, or 6 in. instead of 4 in. This wall was tried against another wall of precisely equal dimensions, but solid throughout: the

42



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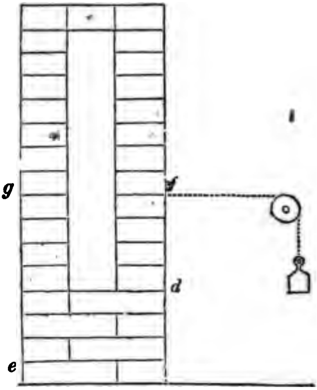


diagrams figs. 42 and 43 are end views of these two walls. The results of the experiments were, that the solid wall (fig. 42) required a lateral force of $5\frac{1}{2}$ lb to balance it; and the hollow wall (fig. 43) required a force of 4 lb to balance it. Now, the weight of the wall fig. 42 was 24 lb, and that of fig. 43 was 18 lb, or one quarter less of material than the other; and the difference between the lateral force, or between $5\frac{1}{2}$ lb and 4 lb, is $1\frac{1}{2}$ lb, which is rather more than a quarter. This shows that what is saved in material is lost in strength; but, at the same time, proves a hollow

wall to be stronger than a pilastered wall, although containing the same quantity of materials.

Let it be here remarked, that, whilst carrying on the experiment with the hollow wall, the lateral force at *f* caused that part of the wall *g* to yield a little inwards; which shows the necessity of preventing this by occasionally introducing bonds. Both of these walls (figs. 42 and 43) gave way towards the bottom courses.

Four other walls were erected, the dimensions and results are contained in the following table, and reference made to the 37th diagram.

Number of walls.	Long.	Thick.	Height.	Weight	Lateral force applied.	Lateral force.
1	16 in.	2 in.	16 in.	8 lb..	At *e*	$\frac{1}{4}$ $\frac{1}{8}$ $\frac{1}{16}$ lb.
2	16	4	16	16	...	$1\frac{3}{4}$ $\frac{1}{8}$
3	16	6	16	24	...	$4\frac{1}{4}$
4	16	8	16	32	...	8 nearly.

It appears from the above table, that the balancing forces of the three latter walls approach the geometric proportions, since their forces are to each other as 2, 4, 8 nearly. Their respective weights are in arithmetical proportion, they having 8 as their common increment.

The proportion of the balancing force to the weight of each wall may be said to be as under: —

Number of walls.	Force.	Weight.	Proportion of wall.
1	$\frac{1}{2}$ lb.	8 lb.	$\frac{1}{16}$ part of the wall.
2	2	16	$\frac{1}{8}$
3	4	24	$\frac{1}{6}$
4	8	32	$\frac{1}{4}$

Now, supposing No. 1 wall to be of 4 in. brickwork, which will give the scale of half an inch to an inch, consequently the height of 16 in. will equal 32 in., equal 2 ft. height. This wall, as shown in the table above, will balance

against a force equal to $\frac{1}{16}$th part of the weight of the wall.

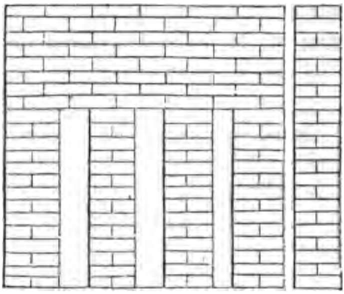
The same will be the case with respect to the other walls, which may be considered as a 9 in., a 14 in., and an 18 in.

Again, let the 4 in., 9 in., 14 in., and 18 in., or any multiple of them be raised to the height of five, ten, twenty, or any other equal number of feet in height, their respective strengths will still be to each other as given in the tables; in fact, rather more with regard to the three latter, because the 9 in. wall exceeds the double of the 4 in. wall by 1 in., and the others in like proportion.

The lateral force in these experiments has been considered as applied at the point *e*, in fig. 37, but if the force is to be applied at either *f* or *g*, the table attached to this diagram will give pretty correctly the proportionate increased quantity of strength.

As many walls are constructed of masonry, with openings for windows and doors, it will not be out of place to introduce here a few more experiments, to show the diminution of strength such walls experience in comparison with a solid wall, when subjected to the same lateral force.

44



First. A solid wall was erected of these dimensions:— 24 in. long, 4 in. thick, and 24 in. high. This wall balanced against a lateral force of $2\frac{1}{2}$ lb, applied horizontally, at the height of 18 in. from the base.

Second. A wall of the same dimensions as the preceding, but having three openings, extending from the base to the height of 15 in., and equalling together 8 in.; or standing indeed on four piers, each of 4 in. square base, and 15 in. high. See diagram, fig. 44. This wall just balanced against a lateral force of 2 lb, applied at the height of 18 in. from the base.

Third. A wall, as before, having however five openings, equalling together 12 in., or standing on six piers, their bases being 4 in. by 2 in., and 15 in. high. This wall just balanced against a lateral force of 2 lb.

From these three experiments, it appears a few openings for windows or doors in a wall does not impair its strength so much as might be supposed; indeed, they prove, again and again, that length of base in comparison with depth adds little to the strength of any wall against lateral force.

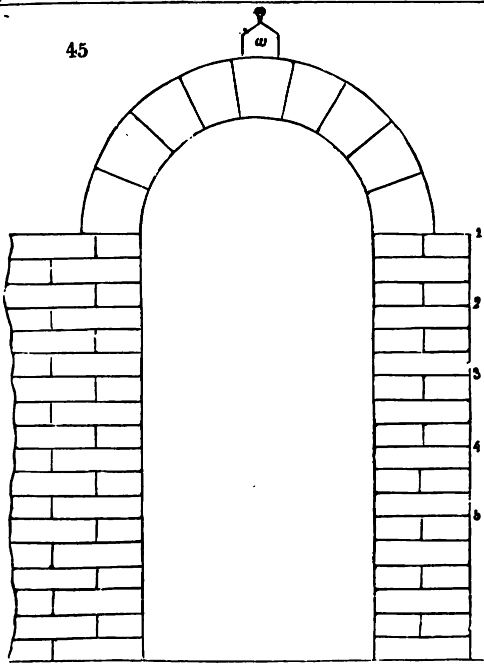
ESSAY IV.

EXPERIMENTS WITH ARCHES PLACED ON PIERS, HAVING WEIGHTS AND STRUCTURES UPON THEM.

First of Arches on Piers, &c.—The scale employed in the following diagrams is one eighth of an inch to an inch; and the wooden voussoirs and bricks are of the same dimensions as those specified in the preceding essays under the same title. The results of the first experiments with figs. 45 and 46 are as follows:—

No. of experiment.	Dimensions of the pier.	Height of the pier.	Weight of the pier.	Span of the arch.	Weight of the arch.	Balancing weight on the arch.	Total weight on the top of the pier, being half the arch and the weight placed on it.
		Relative to Fig. 45.					
1	4 in. by 4 in.	18 in.	$4\frac{1}{2}$ lb.	10 in.	$4\frac{1}{2}$ lb.	$\frac{1}{2}$ lb.	$2\frac{1}{2}$ lb.
2	4 ... 4	15	$3\frac{3}{4}$	10	$4\frac{1}{2}$	$\frac{3}{4}$	$2\frac{5}{8}$
3	4 ... 4	12	3	10	$4\frac{1}{2}$	$1\frac{1}{2}$	3
4	4 ... 4	9	$2\frac{1}{4}$	10	$4\frac{1}{2}$	$3\frac{1}{4}$	$3\frac{7}{8}$
5	4 ... 4	6	$1\frac{1}{2}$	10	$4\frac{1}{2}$	7	$5\frac{3}{4}$
		Relative to Fig. 46.					
6	6 ... 4	18	$6\frac{3}{4}$	10	$4\frac{1}{2}$	3	$3\frac{3}{4}$
7	6 ... 4	15	$5\frac{5}{8}$	10	$4\frac{1}{2}$	$5\frac{1}{4}$	$4\frac{7}{8}$
8	6 ... 4	12	$4\frac{1}{2}$	10	$4\frac{1}{2}$	7	$5\frac{3}{4}$
9	6 ... 4	9	$3\frac{3}{8}$	10	$4\frac{1}{2}$	14	$9\frac{1}{4}$
10	8 ... 4	6	3	10	$4\frac{1}{2}$	*	...

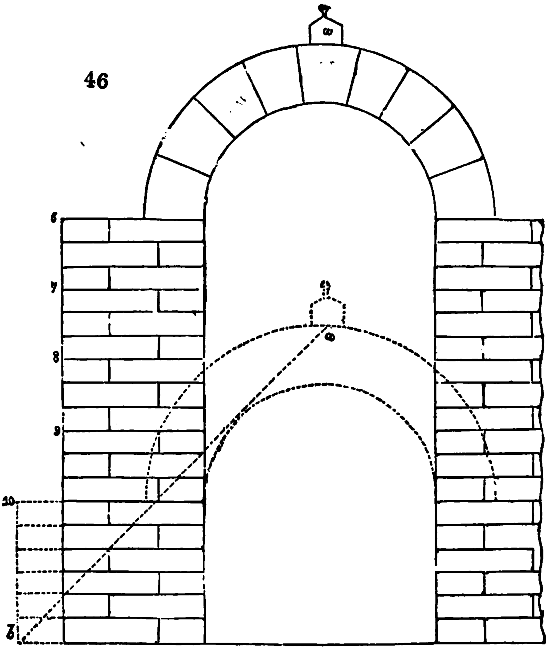
45



* The result here was, that the arch carried my weight (a weight

Fig. 47 is an experiment with a double voussoir arch, placed on a pier, the base of which measures 4 in. by 4 in.,

46



and 12 in. in height; and which answers to the third experiment in the table relative to fig. 45. This double arch, balanced with 1½ lb, as in Experiment 3 (fig. 45), under the single arch, consequently, proving the effects of both, as respects lateral force, to be the same.

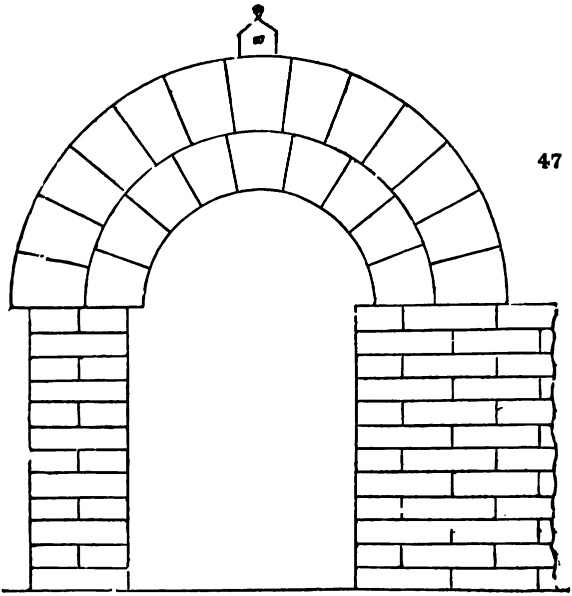
Figs. 48 and 49 are experiments with arches on piers having superstructures raised on them; the following are the results:—

---

equalling 147 lb.), because a straight line could be drawn from the weight at *a*, through the voussoir and pier, to the ground *b*.

Relative to fig. 48.

Weight placed at the numbers, as under.	Courses above the crown of the arch.	Weight of bricks above the arch.	Weight placed on the bricks.	Total weight of superstructure, and the weight on the bricks.	Observations.
2	3 courses.	$3\frac{3}{4}$ lb.	6 lb.	$9\frac{3}{4}$ lb.	The arch sustained this weight well.
3	6	$7\frac{1}{2}$	9	$16\frac{1}{2}$	With this weight, also, it carried all firmly.
4	9	$11\frac{1}{2}$	28	$39\frac{1}{4}$	With this weight it carried all without yielding; and, therefore, could have borne considerably more.



47

After removing the angles of the masonry, as shown in the diagram fig. 49, and replacing the weights as before, the arch and pier had just sufficient strength to support

14 lb. Again, with reference to fig. 48, when the masonry was carried up to the dotted line *a b*, the arch and pier balanced under the weight of 3 lb, placed over the crown at 1; whereas, as shown in the third experiment, relative to

48

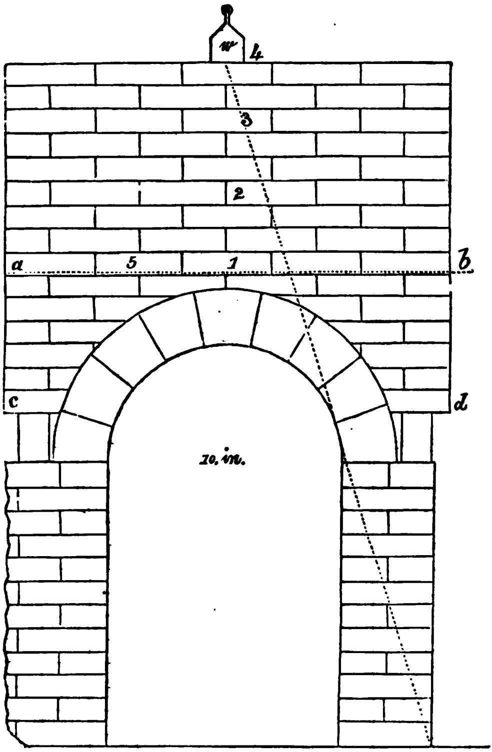


fig. 45, the arch and piers with voussoirs alone, that is, the arch without any superstructure, only carried $1\frac{1}{2}$ lb.

The conclusions which may, therefore, be fairly drawn are, that the higher the masonry is carried, the more an arch or pier will support: a similar result to that which

has before been given in Experiment 10, Essay II. (fig. 14).

When a weight was placed at 5, on the line *a b* (fig. 48), the arch and pier carried 4 lb; which is 1 lb more than when it was placed over the crown of the arch. This proves that the point over the centre of the arch is the weakest part, when the arch is placed on a movable pier.

49

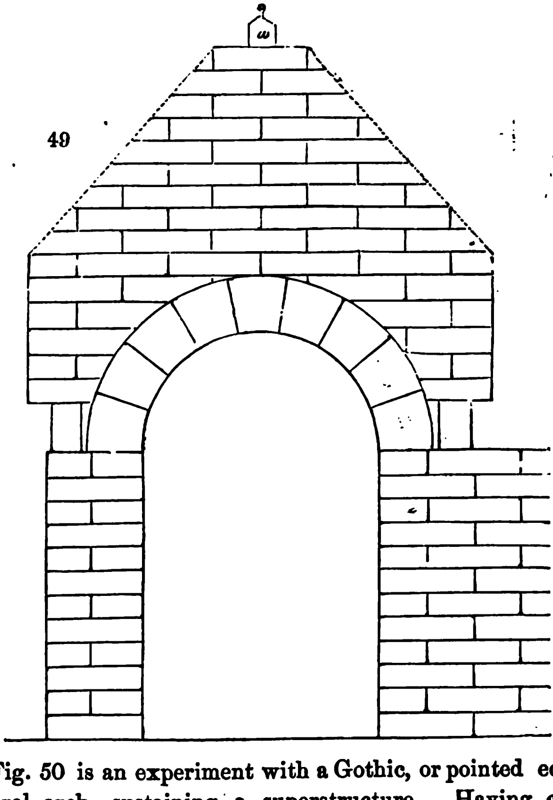
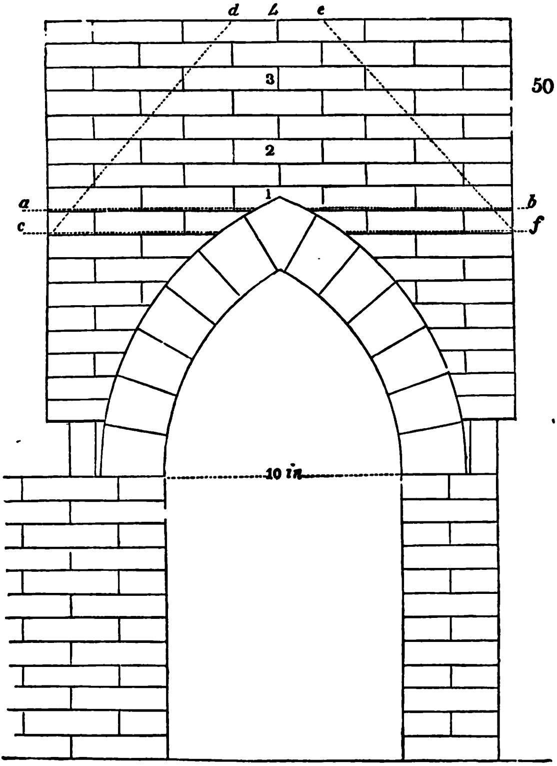


Fig. 50 is an experiment with a Gothic, or pointed equilateral arch, sustaining a superstructure. Having constructed this arch of voussoirs only, and placed it upon piers of the same base and height as the arch fig. 48, it balanced

under the weight of 3¼ lb. On raising the masonry, that is, the wooden bricks, up to *a b*, the arch and pier balanced with 6½ lb, or double of the weight which the arch and pier carried without the masonry. At the point 2, the



structures stood firmly under a weight of 20 lb.; and, at 3, 28 lb were not found too much for the structure to sustain. Upon raising the brickwork up three more courses, and removing the two angles *a d* and *e f*, the arch and pier just balanced under the weight of 28 lb placed at the point 4.

These experiments with the Roman and Gothic arches

show that the latter will support just double the weight of the former, under such circumstances as are described, and as are represented by the diagrams figs. 48, 49, and 50.

A Gothic and a Roman arch, of 10 in. span, composed only of voussoirs, having one end of each supported on the same pillar, or pier, of equal dimensions as that of fig. 48, and placed, not abutting, but at right angles the one to the other, balanced with the following weights on their crowns; namely, the Gothic arch with more than 6 lb, the Roman arch with more than 3 lb.

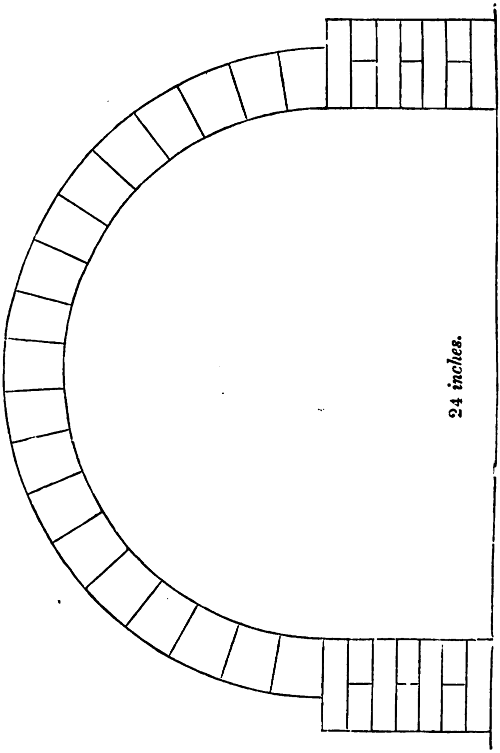
From these results it is manifest, that the stability of the single arch and pier is doubled by having one end of a second arch resting on the same pier, when the lateral force of the latter acts at right angles to the direction of the former.

ESSAY V.

1. EXPERIMENTS WITH ARCHES PLACED ON PIERS, HAVING WEIGHTS AND STRUCTURES UPON THEM.
2. EXPERIMENTS WITH PIERS THAT WILL JUST BALANCE UNDER THE LATERAL FORCE AND WEIGHT OF DIFFERENT ARCHES.
3. EXPERIMENTS WITH ARCHES OF VARIED SPAN AND FORM, ACTING AGAINST EACH OTHER, BEING PLACED ON PIERS OF UNEQUAL AND EQUAL HEIGHTS.

The three following diagrams (figs. 51, 52, and 53) represent experiments with a semicircular arch, and two of its segments, placed on piers of equal bases, to ascertain their respective lateral forces, by the difference of height of the piers on which they respectively will balance.

Fig. 51 represents an arch of 24 in. span, and 19 in. high, and composed of twenty voussoirs, each of the weight of half a pound, which just balanced on piers of 7 in. in height;



51

the base measuring 4 in. by 4 in. The weight of the arch is 10 lb. The height, from the base line to the under part of the keystone, is 19 in.

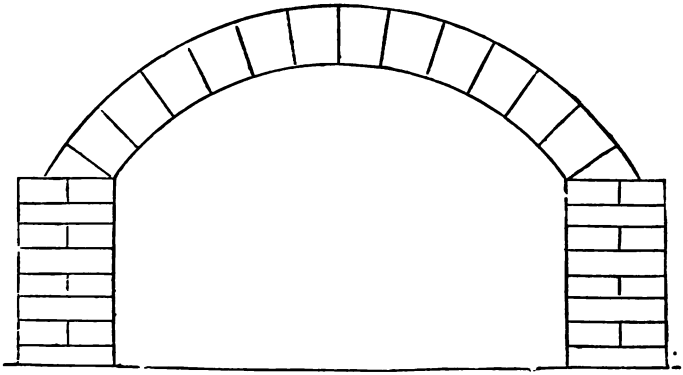
The arch fig. 52 just balances on piers 8 in. high. The weight of the arch is 6 lb.

The arch fig. 53 just balances on piers 7 in. high; and its weight is $4\frac{1}{2}$ lb.

The following are comparisons between the differe
arches of equal span and rise: —

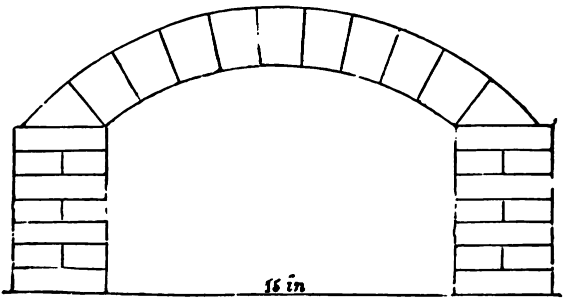
An elliptical arch of 24 in. span, and 8 in. rise, ju
balances on piers 4 in. by 4 in. base, and 5 in. high.

52



A cycloidal arch of 24 in. span, and 8 in. rise, just balances on piers of 4 in. by 4 in. base, and 5 in. high.

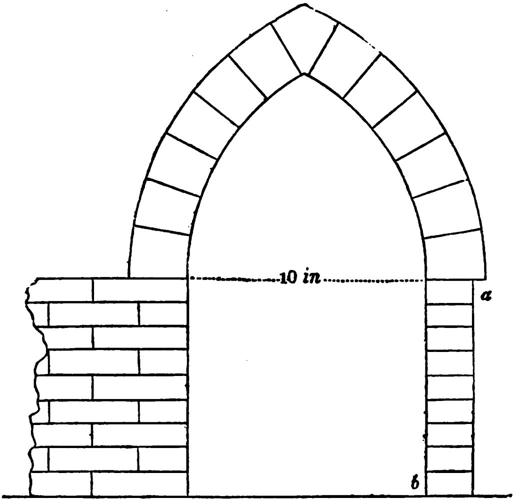
53



A segmental arch of 24 in. span, and 8 in. rise, just
lances, also, on piers of 4 in. by 4 in. base, and 7 in.
gh

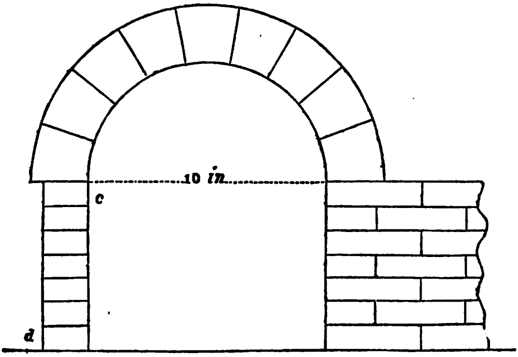
This last experiment with the segment of a circle correctly confirms what was observed of that form of arch

54



when treating of the extrados of the ellipse and cycloid, as given in Essay I.

55

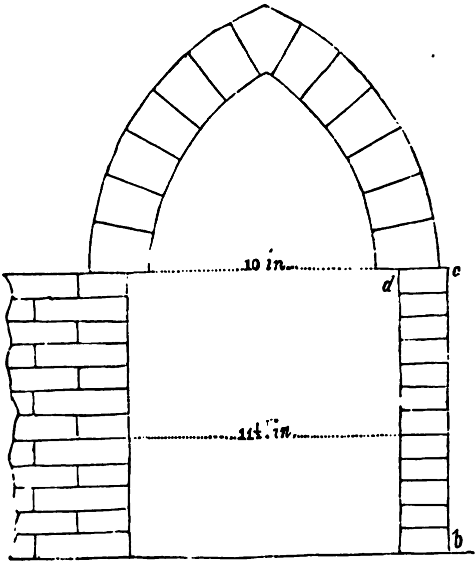


The Gothic and Roman arches of equal spans, being

placed on piers of the same dimensions of base, balance as under: —

Relative to the Gothic Arch, fig. 54.—When the inside of the lowest voussoir coincides with the inside of the pier *a b*, as at *a*, this arch balances on piers 9 in. high; the base measuring 2 in. by 4. in.

56



Relative to the Roman Arch, fig. 55. — When the inside of the lowest voussoir coincides with the inside of the pier (*c d*), as at *c*, the arch balances on piers 7 in. high, the base measuring 2 in. by 4 in.

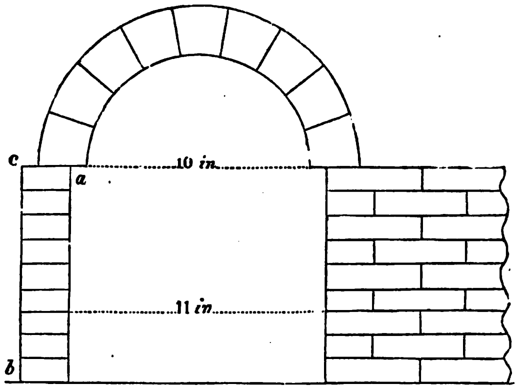
Again, the same two arches, being placed with the intrados of their lowest voussoirs at a certain distance within the line of the piers, balance as follows: —

Relative to the Gothic Arch, fig. 56.—This arch balances on the pier *a b*, which is 12 in. high, having 2 in. by 4. in. for the base. The arch projects within the pier, at *a*, three

quarters of an inch, or it would not balance. When the pier is reduced to 9 in. in height, the arch will carry half a pound; and when reduced to 6 in. in height, it will carry 3 lb well, or twice the weight of the pier of six bricks.

Relative to the Roman Arch, fig. 57.—This arch balances on the pier *a b*, which is 9 in. high; having the same base as fig. 56. The arch projects within the pier, at *a*, half an inch.

57



When the dimensions of the bases of these pillars supporting the Gothic and Roman arches are increased to 4 in. by 4 in., these arches will then balance at the height shown by figs. 58 and 59.

The Gothic arch, fig. 58, balances on the pier *a b*, of 32 in. in height.

The Roman arch, fig. 59, balances on the pier *a b*, of 23 in. in height.

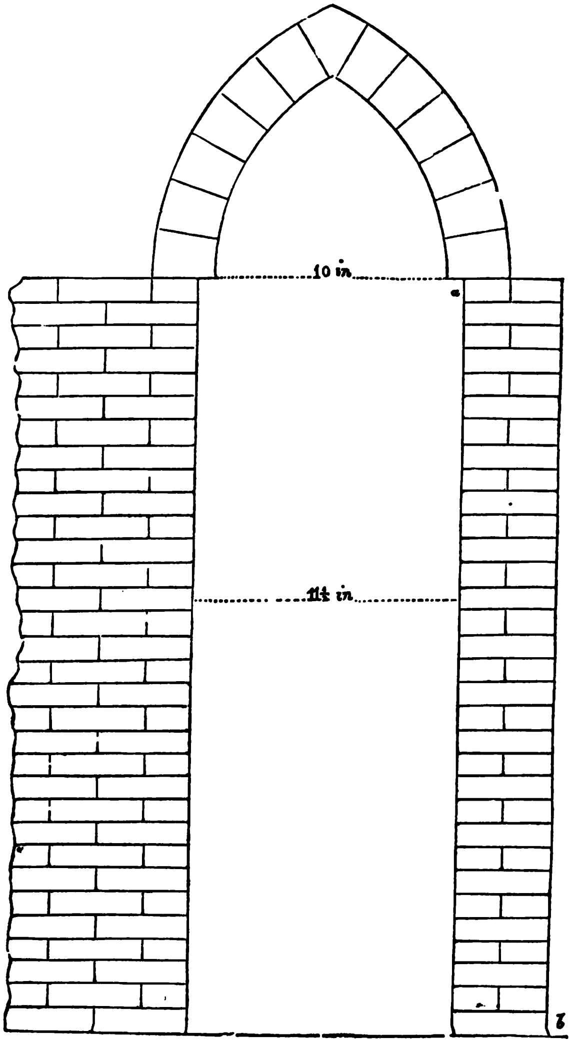
On increasing the dimensions of the piers of these two arches, by making their bases 6 in. by 6 in., and placing them upon the same, the balancing heights were found to be,—

For the Gothic arch, fig. 60, 96 in.

For the Roman arch, fig. 61, 72 in.

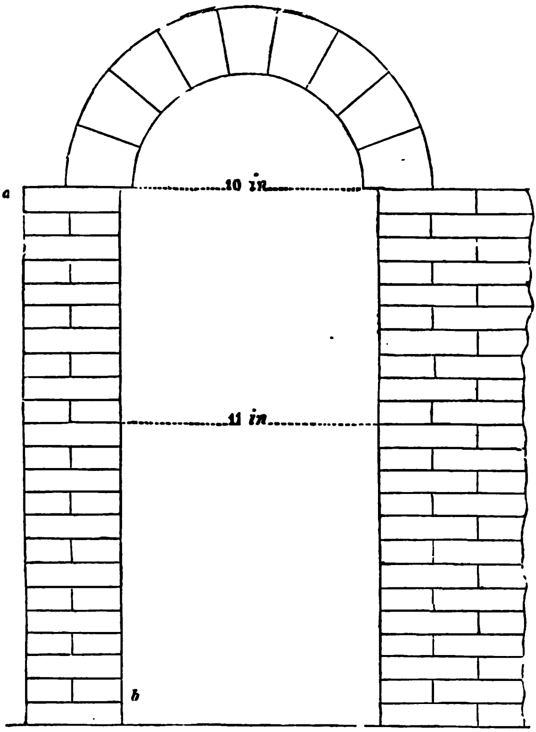
The balancing heights of the Gothic and Roman arches upon the several piers, from fig. 54 to 64, bear the same

58



proportion to each other, within a fraction, throughout the whole of the eight last-mentioned experiments; and this circumstance may therefore be considered as a proof of the correctness of the lateral forces.

59



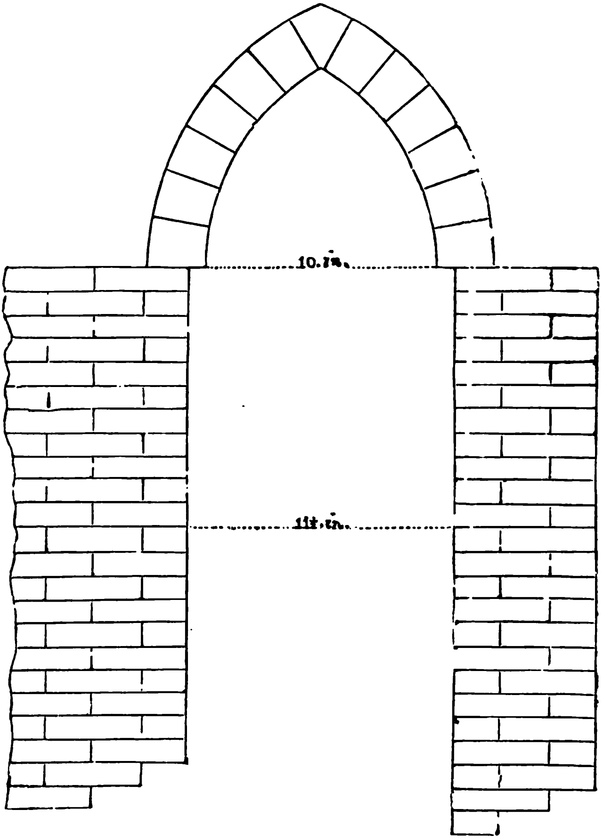
The lateral forces of figs. 54 and 55 are in the proportion of 9 in. to 7 in.

The lateral forces of figs. 56 and 57 are in the proportion of 12 in. to 9 in.

The lateral forces of figs. 58 and 59 are in the proportion of 32 in. to 23 in.

The lateral forces of figs 60 and 61 are in the proportion of 96 in. to 72 in.

60



Again, with regard to the pillars, or piers, to the balancing heights: —

Relative to the Gothic Arch.

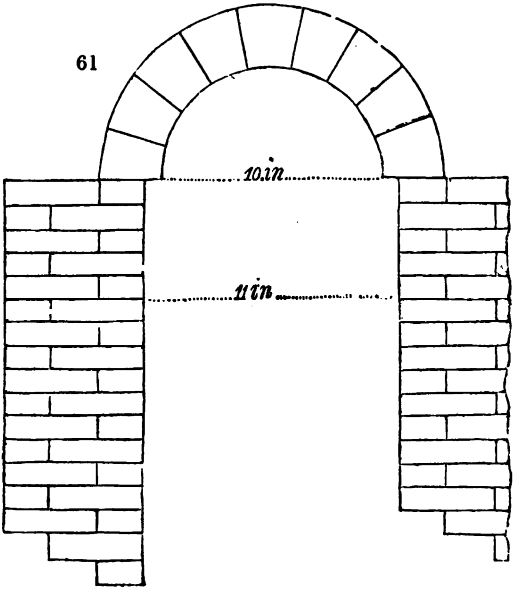
Fig. 54, the proportion is as 2 in. to 9 in., not quite one fifth.

Fig. 56, the proportion is as 2 in. to 12 in., or one sixth.

Fig. 58, the proportion is as 4 in. to 32 in., or one eighth.

Fig. 60, the proportion is as 6 in. to 96 in., or one sixteenth.

61



Relative to the Roman Arch.

Fig. 55, the proportion is as 2 in. to 7 in., not quite one quarter.

Fig. 57, the proportion is as 2 in. to 9 in., or nearly one fifth.

Fig. 59, the proportion is as 4 in. to 23 in., or nearly one sixth.

Fig. 61, the proportion is as 6 in. to 72 in., or one twelfth.

Of the diameter of the pier to the span.

Relative to the Gothic Arch.

Fig. 54, the proportion is as 2 in. to 10 in., or one fifth.

Fig. 56, proportion as 2 in. to 11½ in., or nearly one sixth.

Fig. 58, proportion as 4 in. to 11½ in., or nearly one third.

Fig. 60, proportion as 6 in. to 11½ in., or nearly one half.

The proportions, in this respect, of the Roman arch are all less than the above.

Of the proportions between the span of the arch and the balancing height of the pier.

Relative to the Gothic Arch, beginning with fig. 56.

Fig. 56, the proportion is as 11½ in. to 12 in., or nearly as 1 to 1.

Fig. 58, the proportion is as 11½ in. to 32 in., or nearly as 1 to 3.

Fig. 60, the proportion is as 11½ in. to 96 in., or nearly as 1 to 8.

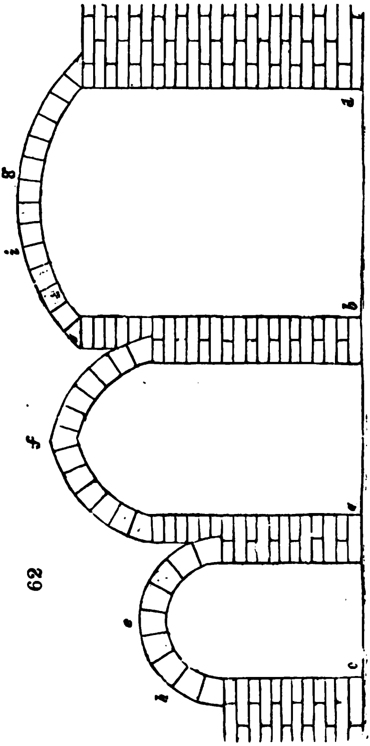
The proportions of the Roman arch, as to span, and height of pillar, are not so regular as the Gothic.

The superiority of the Gothic over the Roman arch, in regard to the greater lightness of pillar, sufficiently accounts for the general preference given by our forefathers to the pointed form; and, at the same time, justifies their adoption of it in the construction of our most celebrated cathedrals.

The following are experiments with arches of unequal span, and of dissimilar forms, placed on piers of different heights, and supported between two immovable buttresses: —

The spans of the arches *e*, *f*, and *g* (fig. 62) are 10 in., 13 in., and 19½ in. respectively. The bases of the two movable piers measure each 4 in. by 4 in.: *c* and *d* are the

immovable piers, or buttresses. The heights of the piers are 12 in., 18 in., and 24 in. respectively.



62

Now, when a weight of $1\frac{3}{4}$ lb was placed on the crown of the arch *g*, it caused the arch *f* to fly up, by the pier *b* being forced in. A 1 lb weight, placed on the arch *f*, just balanced a 2 lb weight placed on the arch *g*, but caused the arch *e* to open very much at *h*; and half a pound more being added to the 2 lb on the arch *g*, caused both the arches *e* and *f* to fly up: the arch *e* had no weight on its crown. A weight of $9\frac{1}{2}$ lb being placed on the crown

of the arch *e*, caused the arch *f* to fly up, there being no weight upon the crown of the latter. A weight of $4\frac{1}{4}$ lb, placed on the arch *f*, caused the arch *e* to fly up, there being no weight on its crown. Upon adding a quarter of a pound more to the weight on the crown of the arch *f*, thus making the whole weight $4\frac{1}{2}$ lb, the pier *b* of the arch *g* was forced down; the arch *e* having been previously prevented from falling, by the pressure of the hand on its crown.

Again, when these three arches (*e*, *f*, and *g*) were placed upon piers all of the same height, of 18 in., with the same base, of 4 in. by 4 in., as in the preceding experiments, but the span of the arch *f* altered from 13 in. to 15 in., and having a rise of 5 in., the same as the other two arches, the results were as follows: —

A weight of $1\frac{1}{4}$ lb, placed on the crown of the arch *g*, caused the arch *e* to fly up. A weight of $1\frac{3}{4}$ lb, placed on the crown of the arch *f*, also caused the arch *e* to fly up; and, when a weight of 10 lb was placed on the crown of the arch *e*, it caused the arch *g* to fly up. During these three experiments, there were no other weights on the crown of the arches besides those used to make the trials, and placed as above stated.

The conclusions to be drawn from all the experiments with the three arches (*e*, *f*, and *g*, fig. 62) and their piers are, that, where there is equal and similar pressure, there should be equal and similar arches and piers to meet it.

It may be observed, that the point *i* in the arch *g* of the last-mentioned figure will carry a greater weight than the crown; therefore, again proving that arches supported on piers are weakest at the crown.

The following are experiments with two Roman arches, of 10 in. span (fig. 63), one end of each resting on immovable buttresses, but having the two ends which abut placed on a movable pier, varied to different heights and dimensions: —

Number of experiment.	Dimensions of the pier.	Height of the pier.	The weight on the top of the arch with which it balanced.
No. 1	1 in. thick	6 in. high.	3 lb.
2	2	6	8
3	4	6	28
4	1	12	$2\frac{1}{2}$
5	2	12	$4\frac{1}{2}$
6	4	12	8
7	1	18	$1\frac{5}{8}$
8	2	18	$3\frac{1}{4}$
9	4	18	$6\frac{1}{2}$

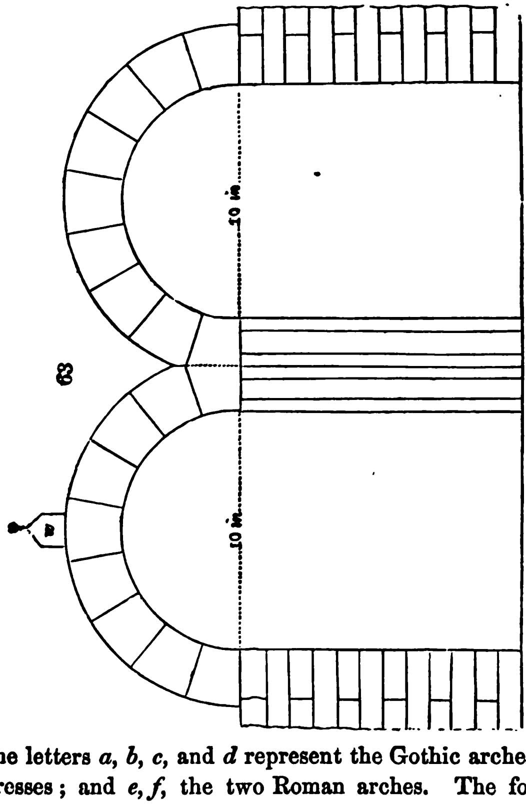
Fig. 64 represents two Gothic arches, of 10 in. span, placed the same as the preceding two Roman arches; and the following are the results of the experiments: —

Number of experiment.	Dimensions of the pier.	Height of the pier.	The weight on the top of the arch with which it balanced.
No. 1	1 in. by 4 in.	6 in	$4\frac{3}{8}$ lb.
2	2 ... 4	6	14
3	4 ... 4	6	28 almost as nothing.
4	1 ... 4	12	$2\frac{1}{2}$
5	2 ... 4	12	6
6	4 ... 4	12	14
7	1 ... 4	18	2
8	2 ... 4	18	4
9	4 ... 4	18	8

The piers for the first, fourth, and seventh experiments in the last two diagrams, were made with solid pieces of board, 1 in. thick, 4 in. broad, and of the heights of 6 in., 12 in., and 18 in., respectively: bricks were employed for the other piers. With respect to the difference between the strength of a solid pier and one composed of several pieces, it is in favour of the former.

Fig. 65 represents experiments with four arches; two of Roman, and two of Gothic construction, of equal spans of 10 in., and placed upon a single pier in the centre, having immovable buttresses; the two Roman arches abutting

against each other, and at right angles to the two Gothic arches.

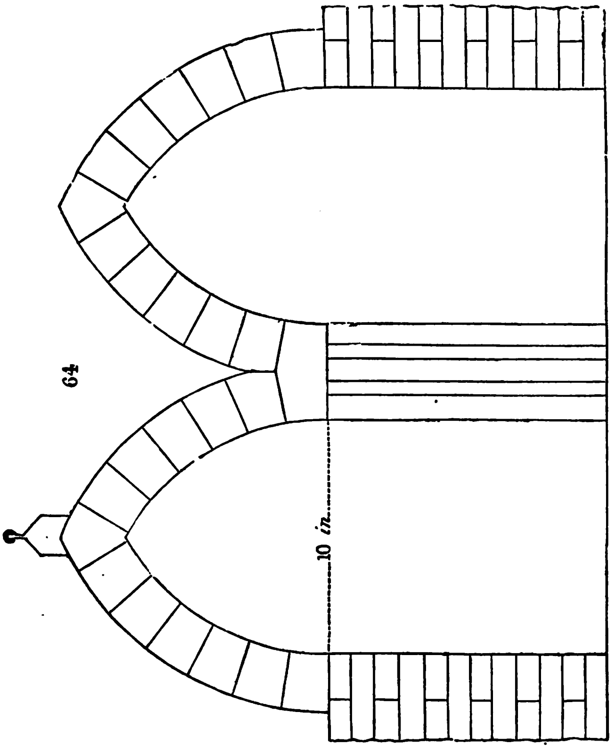


The letters *a*, *b*, *c*, and *d* represent the Gothic arches and buttresses; and *e*, *f*, the two Roman arches. The following are the results: —

Number of experiment.	Dimensions of the pier.	Height of the pier.	The weight on the top of the arch with which it is balanced.
No. 1	1 in. by 4 in. board.	12 in.	4 lb.
2	1 ... 4	12	4
3	1 ... 1 stick.	12	4
[illegible]	1 ... 1	12	4

The Roman and Gothic arches just balanced with the same weight.

In the first and second experiments, the pier was composed of a piece of board of 1 in. by 4 in., and 12 in. high. On a pier of these dimensions, both the Roman and Gothic arches balanced with the same weight; and, when a round stick of 1 in. in diameter was substituted for the board, the four arches, also, balanced with 4 lb on the top.



On comparing these experiments with the two numbers 4 of the two preceding diagrams (figs. 63 and 64), it will be seen that in both instances the arches just balanced

with the same weights of $2\frac{1}{2}$ lb placed on their crowns; whereas, in the diagram of the four arches (fig. 65), the weight of 4 lb was required to cause the arches to balance; or nearly twice as much as either of the double arches.

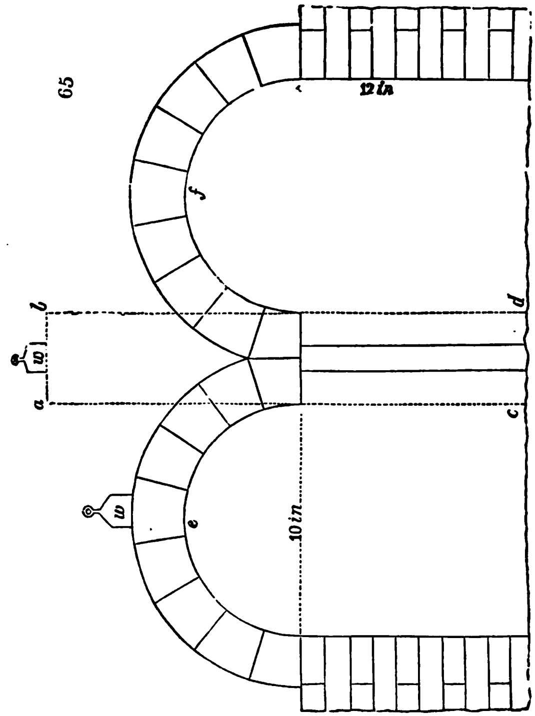
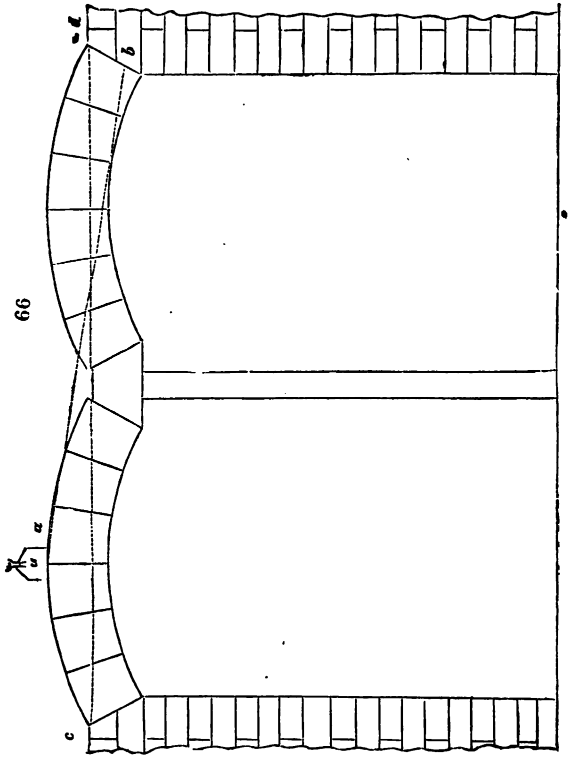


Fig. 66 represents experiments with two flat arches of equal span, each composed of six voussoirs; and spanning nearly 12 in. The pier, which was 1 in. thick, and 18 in. high, being composed of a piece of board of the dimensions of 1 in. by 4 in., and 12 in. high. Three 1 in. by 2 in. bricks were then placed edgewise up the remaining 6 in.

These two arches (fig. 66) balance with 21 lb on the top of either of them; and this weight far exceeds that

supported in the experiments of the diagrams figs. 62 and 63.

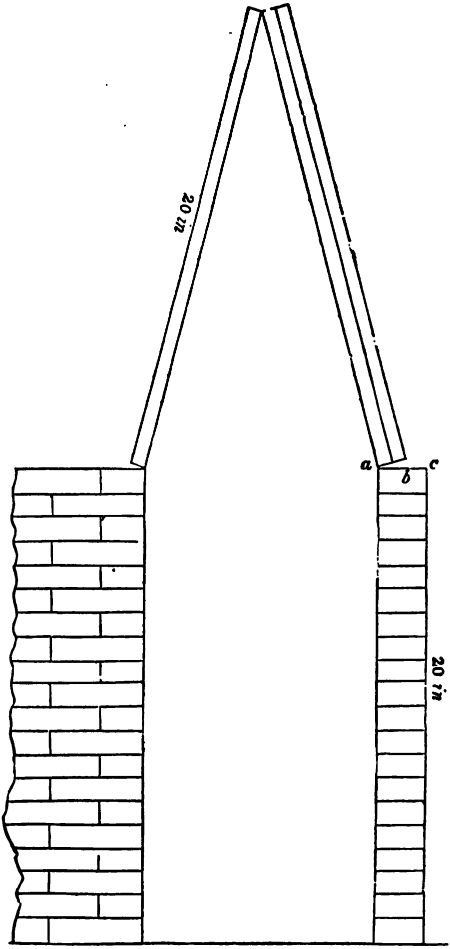


66

This superior strength is to be attributed chiefly to the being able to draw a straight line, as *c d* (fig. 66), passing through, or rather within, the voussoirs of both arches, from one buttress to the other; and, if the space between the two arches, just over the pier, be built up level with the crowns of the arches, and made all solid, a straight line might then be drawn from *a* to *b*, which would be within the voussoirs and masonry. Let it, however, be remem-

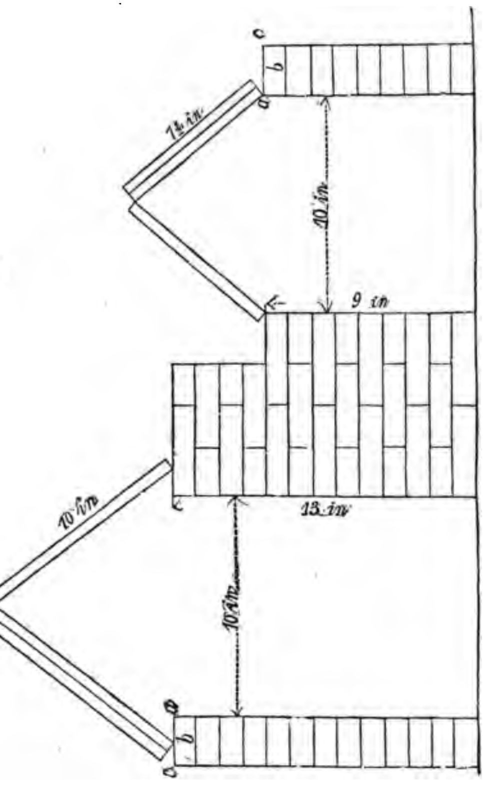
bered that the buttress must be immovable, or the arches will support very little.

67



In the diagrams figs. 63 and 64 the greatest height of the piers, or pillars, does not exceed 18 in., which is just

twice the balancing height of the pier *a b* of the Roman arch fig. 57. Now, on increasing the pillar to 36 in., or four times the balancing height, having the same dimensions of base (4 in. by 2 in.), composed of wooden bricks, and cor-



68

responding to the piers numbered 2, 5, and 8, in the table relative to fig. 63, either arch carried the weight of 1¼ lb on the crown. Upon substituting a solid pier instead of the brick one, either arch carried nearly 2½ lb. It has been before observed, that eight of these wooden bricks weigh

1 lb; therefore the pier in the diagram fig. 57 equals rather more than $1\frac{1}{8}$ lb: consequently, when the pier is carried up four times the height, and is, therefore, four times the weight, the Roman arches, resting upon this movable pillar, and abutting each other, support the weight of nine bricks, or a fourth part of the pier of 36 in. in height.

The Gothic arches, when placed under such circumstances as the above, but with the pillar 48 in. high, carry the balancing pier of diagram fig. 56, which is composed of twelve bricks; and with a solid pier they carry the weight of twenty-four bricks, or half of the whole pier.

Experiments to show the Laws of the Pressure of Roofs on Walls.—The walls, or piers, represented in the diagrams figs. 67 and 68, are composed of wooden bricks, 2 in. wide by 4 in. long; and the roofs are boards, from half an inch to 2 in. in thickness, that rest upon the whole length of the bricks, which is 4 in. The walls are built up to the height on which the roofs, according to their thickness, will balance. The following are the results of the different experiments:—

Experiments.	Balances on the wall.	Height of wall, and observations.
	Roof 20 in. long, and ½ in. thick.	
No. 1	Balances inside at *a*.	20 in. high.
2	middle at *b*.	11
3	outside at *c*.	2
	Roof 20 in. long, and 1 in. thi	
4	Balances inside at *a*.	20 in. high.
5	middle at *b*.	10
6	outside at *c*.	2
	Roof 20 in. long, and 2 in. thick.	
7	Balances inside at *a*.	Forced the wall inwards.
8	middle at *b*.	10 in. high.
9	outside at *c*.	1

Experiments.	Balances on the wall.	Height of wall, and observations.
	Roof 10 *in. long, and* $\frac{1}{2}$ *in. thick.*	
10	Balances inside at *a.*	13 in. high.
11	middle at *b.*	8
12	outside at *c.*	...
	Roof 10 *in. long, and* 1 *in. thick.*	
13	Balances inside at *a.*	9 in. high.
14	middle at *b.*	4
	Roof $7\frac{1}{2}$ *in. long, and* $\frac{1}{2}$ *in. thick.*	
15	Balances inside at *a.*	9 in. high.
16	middle at *b.*	4
	Roof $7\frac{1}{2}$ *in. long, and* 1 *in. thick.*	
17	Balances inside at *a.*	7 in. high.
18	middle at *b.*	3

From the above experiments it appears, that the weight of a roof is of less consequence than the place of its bearing, and its pitch, or angle of elevation.

Experiments made for the Purpose of ascertaining and exhibiting the necessary Strength of Piers to be employed at the Angles of Buildings, carrying Arches over Doors and Windows.

Experiment 1. A semicircular arch of 10 in. span just balances on a pier measuring 2 in. by 4 in. for the base, and 7 in. high. See fig. 55.

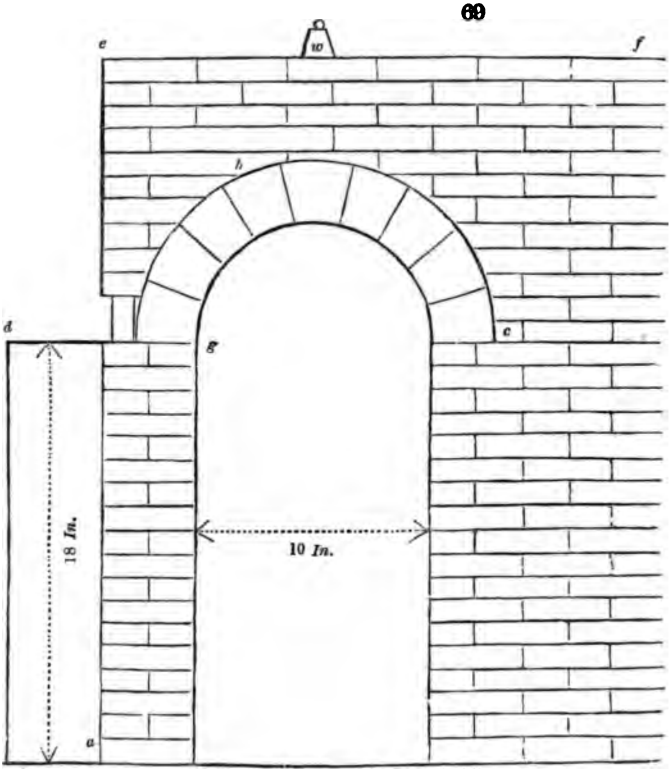
Exper. 2. The same arch, on a pier 4 in. by 4 in. base, and 7 in. high, balances with 5 lb placed on the crown of the arch.

Exper. 3. The same arch, on a pier 2 in. by 4 in. base, as in experiment No. 1, and 7 in. high, having three courses of masonry above the crown of the arch, balances with 5 lb placed on the masonry; thus proving that the strength of the pier in this third experiment is rendered equal to the

pier in the second experiment, by the three courses of masonry above the arch.

Exper. 4. A semicircular arch of 10 in. span just balances on a pier measuring 4 in. by 4 in. base, and 18 in. high. See fig. 69, *a b c*.

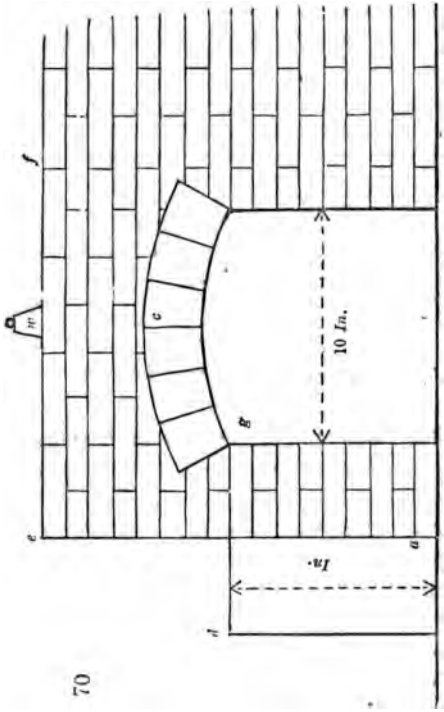
69



Exper. 5. With the pier 9 in. by 4 in. base, and 18 in. high, as represented in the diagram fig. 69 by the letters *a d b c*, balanced with 12 lb on the crown of the arch.

Exper. 6. The pier 4 in. by 4 in. base, the same as in the fourth experiment, and 18 in. high, having four courses of

masonry over the arch, as shown in the same diagram by the letters *a e f*, balances with 12 lb placed on the masonry above the crown of the arch. Here, again, the pier *a b* is rendered equal in strength to the double pier *a d*, against the outward thrust of the arch *g b c*, by the masonry *g e f c*, upon and above the arch.



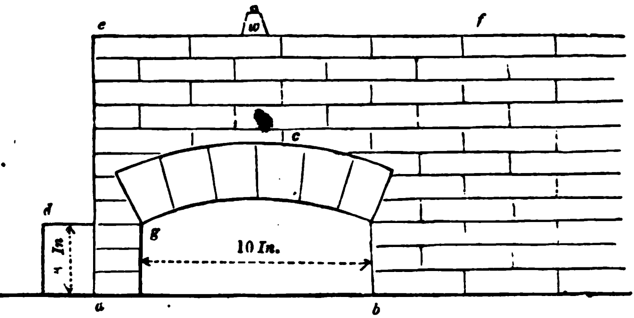
70

Exper. 7. An arch, the segment of a circle, of 12 in. radius, and 10 in. span, just balances on a pier having 4 in. by 4 in. for its base, and 9 in. high. See diagram fig. 70, *a b c*.

Exper. 8. The same arch as the preceding, placed on a pier having a base of 8 in. by 4 in., and 9 in. high, just

balances with 6 lb placed on the crown. See diagram fig. 70, *a d c b*.

Exper. 9. The segment arch, as before, and placed on a pier having 4 in. by 4 in. for its base, and 9 in. high, but with four courses of masonry over the crown of the arch, just balances with 6 lb on the top. (See diagram fig. 70, *a e f b*.) These four courses of masonry, again, render the pier *a g* of equal strength to the double pier *a d g*.



71

Exper. 10. The same segment of arch and span as the preceding just balances on a pier 2 in. by 4 in. for the base, and 3 in. high. See diagram fig. 71, *a b c*.

Exper. 11. The same as experiment 10, but with the base of the pier 4 in. by 4 in., as shown in the diagram fig. 71, by the letters *a d c b*. This arch just balances with 2 lb on the top of the crown.

Exper. 12. The same arch and pier as experiment 10, and of the same height, but having four courses of masonry over the crown (see diagram fig. 71, *a e f b*); and just balances with 2 lb on the top.

Exper. 13. The same segment arch, with a pier 2 in. by 4 in. for its base, but 18 in. high. This arch and pier would not stand even with eight courses of masonry over the crown; the pier being too slight, yielding out immediately, and letting down both arch and masonry.

Exper. 14. The same segment of arch, with the base of the pier 4 in. by 4 in., and 18 in. high; having, as in the preceding experiment, eight courses of masonry over the crown of the arch; but this would not stand, the pier yielding out as before, and letting down both the arch and the incumbent masonry.

Exper. 15. The same arch again, but with 8 in. by 4 in. for the base of the pier, and 18 in. high. Thus constructed, the pier and arch balanced firmly with 3 lb on the crown of the arch.

Exper. 16. The same construction as in experiment 15, but having eight courses of masonry above the crown of the arch. With this masonry so placed, the pier and arch stood without the least yielding under the weight of 12 lb on the top. The reason of this strength proved, upon measurement, to be, that a straight line could be drawn from the weight to the outer base of the pier, quite within all the masonry.

Exper. 17. A pier, or rather wall, 2 in. thick by 16 in. long, and 3 in. high, having the segment arch, as in experiment 10, placed on the top, balanced rather more firmly than it did with that pier; thus proving a portion of strength, though small, to be gained by placing an arch upon a wall where a pier of greater depth cannot be constructed. See similar results, as given in figs. 20 and 21.

The diagrams to which these experiments are referred are on the before-employed scale of the eighth of an inch to an inch; and of the bricks, eight weigh a pound.

ESSAY VI.

RELATIVE TO THE PRACTICAL APPLICATION OF THESE PRINCIPLES.

As the principles of arches and piers, &c., given in the preceding essays, from the results of many experiments, are thus far unfolded to view, the correctness of those principles, relative to practical architecture, remains to be shown. This I shall now attempt to do, by applying them to a few of the ancient and modern structures at present existing in this country. The plan of proceeding I have decided upon is as follows: —

First. To select for examples the common barrel drain, the steening required for a well; the masonry of an oven, a few single arches, and a tunnel.

Secondly. To apply them to the architecture of small churches.

Thirdly. To bridges of more than one arch, among which are some of the noblest works of modern days.

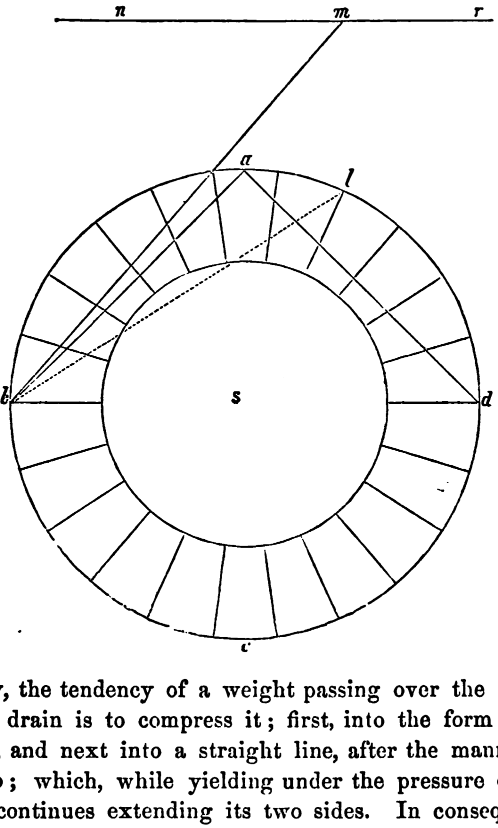
Lastly. To examine by them one or two of the most splendid chapels and cathedrals.

When all this is accomplished, the reader, it is anticipated, will be enabled to inquire for himself, and apply the principles here laid down to other architectural fabrics which he may be desirous of examining, whether they are bridges, churches, or cathedrals; and, should any difficulties arise, a few wooden models of arches and bricks, for experiments, will quickly remove them.

The Barrel Drain. — The explanatory diagram (fig. 72) is to a scale of an $\frac{1}{8}$ in. to 1 in. Let $a\ b\ c\ d$ be a vertical section of a barrel drain, constructed of 4 in. voussoirs in brickwork, and the opening (s) 12 in. in diameter. These

structures are placed underground, and have generally a roadway over them.

72



Now, the tendency of a weight passing over the crown of the drain is to compress it; first, into the form of an ellipse, and next into a straight line, after the manner of a hoop; which, while yielding under the pressure of the hand, continues extending its two sides. In consequence of the lower half of the drain (*b c d*) being based on the solid earth, it cannot in any way yield; thus leaving for consideration only the upper half (*b a d*), which forms a semicircular arch.

This arch having the solid earth for its foundation and buttresses, cannot yield outwardly. From *a* to *b*, and from

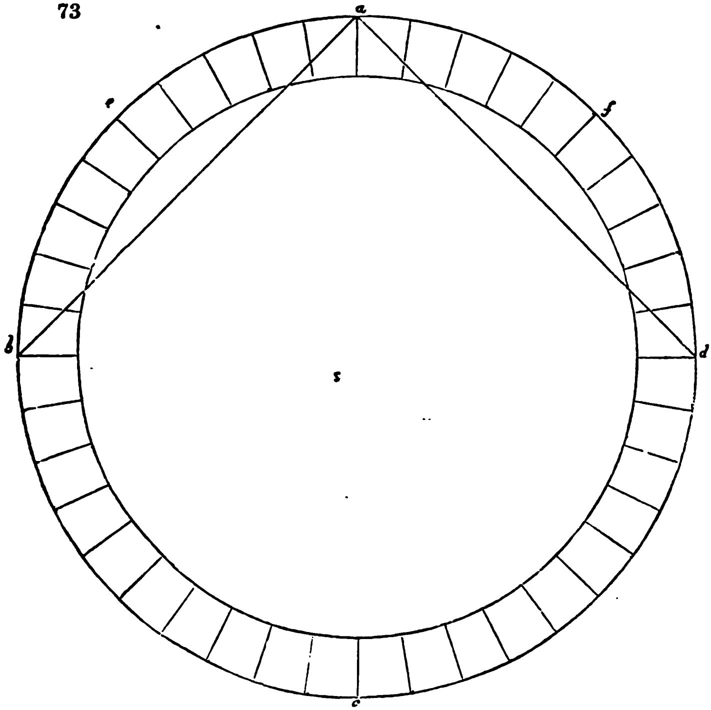
a to *d*, draw the straight lines *a b*, and *a d*: these lines fall within the voussoirs; therefore, the drain will carry any weight placed at *a*, as shown by Ex. Eleventh, Essay II. p. 19. This being a single arch, with deep voussoirs, its weakest point is at *l*; for, when the straight line *l b* is drawn, it lies without the voussoirs; and, therefore, a great weight would cause the arch to fly up between *l* and *b*. It has been before observed, that such drains are placed underground; and, when so situated, they have a portion of soil above them, from 6 in. to 1 ft. or more; if we say 6 in., then the point *l* will be carried up to the line *m n r*, being the supposed surface of the ground. Let *m b* be joined, then the straight line thus formed falls within the voussoirs; consequently, the arch will support, in this case, any weight short of crushing the materials. (See Ex. Ninth, Essay II. p. 16.)

Of the Steening, or Masonry, of a Well, to prevent the Sides from falling in.—The diagram fig. 73, is to a scale of 1 in. to 1 ft. Let *a b c d* be a horizontal section of a well with its masonry; *s*, the shaft, 3 ft. in diameter; and *a b c d*, the brickwork, 4 in. thick, as voussoirs.

Suppose a mass of earth, at the point *a*, were to become loose, it would fall in, but for the masonry. The tendency of the earth against the steening at *a* is the same as the weight on the barrel drain; namely, to compress the steening in at *a*, and a tendency to cause the sides *b d* to extend outwards: but they cannot extend outwards, because of the immovable bank of earth forming the sides of the well. The steening having these immoveable buttresses at *b* and *d*, the part *b a d* may be considered as a semicircular arch. Draw the straight lines *a b*, and *a d*; but, as *a b* and *a d* fall without the voussoirs, the tendency of the pressure at *a* will be to force out the arch-stones at *e* and *f*: here again, however, the effort is resisted by the immovable bank forming buttresses. This would be the case at every point of the steening; consequently, a true equilibrium is maintained

throughout the steening against any outward pressure; the truth of which every old well confirms.

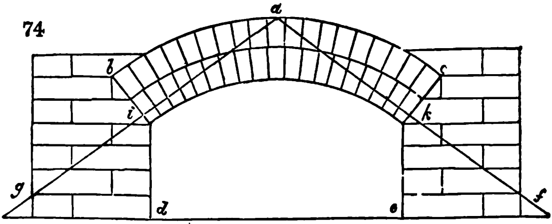
73



Of the Oven.—The scale of the diagram fig. 74 is half an inch to a foot. Let *a b d e c* be a vertical section of a common oven; *b a c*, the crown; and *b d* and *e c*, the sides. This crown, *b a c*, is an arch of 6 in. rise and 3 ft. span, constructed with two courses of 4 in. brickwork, as voussoirs. The sides (*b d* and *c e*) act as piers, and are 14 in. in thickness, and 12 in. high, also of brickwork. From *a*, draw the straight lines *a i* and *a k*, and extend them to the ground at *g* and *f*. Now, *a i* and *a k* lie within the vous-

soirs; therefore, the arch alone will carry any weight on *a*; but, since *a i* and *a k*, when continued, fall without the masonry of the piers, the latter would be overturned by a great weight on *a*. The strength of the piers then remains the object of inquiry.

74



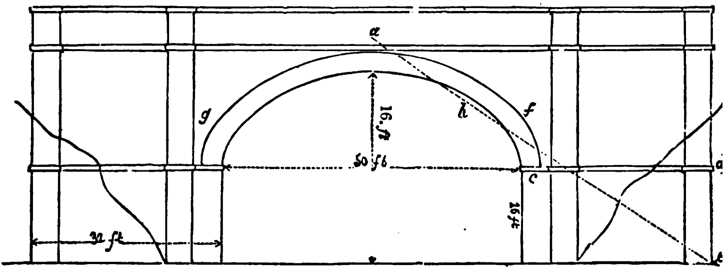
The arch, fig. 53 (Essay IV. p. 52), corresponds in dimensions with the crown of the oven. This arch balances on piers 7 in. high and 4 in. in base, or nearly double in height the thickness of the base, which is nearly ¼ of the span. Now, the sides of the oven, acting as piers, are rather less in height than their thickness of base, which, in this instance, almost equals ⅜ of the span; consequently, they will support the crown of this oven very firmly, having no great extra weight placed at *a*. The thickness of the masonry of the crown and sides is quite necessary, in another point of view; namely, to hold and economise the heat of baking.

Of single Arches.—The new bridge at Loose, near Maidstone, which crosses a valley, is of one arch, and is constructed of stone for the outside casing, having brick in the interior. The dimensions, as nearly as I could obtain them during heavy rain, are as marked in the engraving fig. 75, which is to a scale of one eighth of an inch to two feet.

The roadway (*a*) is 24 ft. wide, and runs horizontally over the bridge, the earth at the two ends forming butresses. This bridge was put to the test of experiment by means of a model of wooden voussoirs and bricks, on the scale of half an inch to a foot, and constructed of one third of the true

width, or 8 ft. instead of 24 ft.; having the piers 28 ft. in thickness, which is the outside measurement. How far the inside is solid masonry, I could not ascertain. This model arch carried at *a* 18 lb; but, on 2 lb more being added, it caused the arch to drive away the masonry on the line *c d*. The dotted line *a e* falls without the voussoirs and masonry at *h*.

75



With respect to the weight of 18 lb on the crown of the model bridge arch, and the proportionate weight on the real bridge, they are as follows:—Of average stonework, about 15 cubic feet go to a ton. Now, in the wooden voussoirs employed, 160 cubic half inches equal $\frac{1}{2}$ lb; and, for the sake of even numbers, say $\frac{1}{2}$ lb equals 10 tons. The model arch, then, by carrying 18 lb, supported a weight in the proportion of 360 tons upon one third of the whole arch.

Nothing has here been said respecting the two banks and road, forming buttresses at each end of the bridge: they, of course, contribute very materially to the strength of the structure; because straight lines may be drawn from any part over the arch, that will pass within the masonry and blanks.

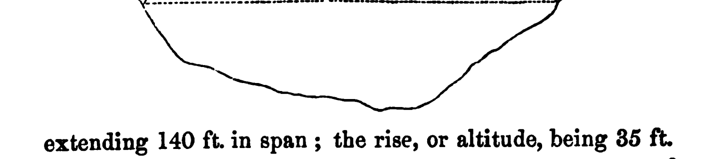
The weight which is liable to be drawn over a bridge of this kind may be ascertained thus:—A waggon, on an average, equals 1 ton in weight, and, when laden with 12 quarters of wheat, at 60 lb a bushel, equals 2 tons 12 cwt.; and, being drawn by four horses, say 8 cwt. each, equals

1 ton 12 cwt.; or, all together, under 6 tons. Let it be possible for a load to go over the bridge equalling 12 tons; this load would take up one third of the width of the roadway. Now, it has been shown that one third of the bridge will carry 360 tons, or 30 times 12 tons.

With the view of ascertaining what weight the bridge would carry without opening the joint at the keystone, a vessel of paper was suspended in the angle of the joint, being inserted $\frac{1}{2}$ in. up the joint on the outside, and 1 in. along the joint underneath. The arch carried 6 lb on the crown; but a greater weight caused the paper to fall down by the opening of the joint underneath. Now, 6 lb multiplied by 20 (the number of tons which 1 lb in the model represents) gives 120 tons; therefore proving most satisfactorily that the strength of this bridge is many times greater than the weight of any load which can possibly be drawn over it; and this, too, independently of the two banks, which act as buttresses.

Ponty Prydd Bridge.—This bridge, in Glamorganshire, represented by fig. 76, which was designed and constructed by an uneducated architect (William Edwards), is of one arch,

76



extending 140 ft. in span; the rise, or altitude, being 35 ft. The arch forms the segment of a circle, the diameter of which is 170 ft. It was completed in the year 1755. (See Malkin's *South Wales.*)

The engraving is correct in the proportions of span and rise of this famous arch, having *d* and *g*, the buttresses, of living rock, and therefore immovable. The depth of the voussoirs, or the thickness of the masonry of the bridge at the crown (*a*), is not given by Mr. Malkin. This arch was put to the test of experiment by a model made of wooden voussoirs. The scale being of a quarter of an inch to a foot, allowed 10 ft. for the depth of the voussoirs, which dimension is adopted in the elevation (fig. 76). Now, the arch, so constructed, carried 8 lb placed on the voussoirs at *e*: more than this weight caused the opposite part of the arch to fly up at *f*. According to the scale of the model, 8 lb equals 540 tons.

It appears from Mr. Malkin's account, that Mr. Edwards's first bridge of one arch fell down; which was caused, as the architect supposed, by there being too great a weight on the haunches at and between *b g* and *c d*, that forced the crown up. In consequence of this, Mr. Edwards, on the reconstruction, caused holes to be left at 1, 2, 3, to lessen the weight at those parts; and the bridge now stands very well. Whether the depth of the voussoirs, or the thickness of masonry at the crown, was increased or not, there is no mention made. The width of the roadway is also omitted; but the wooden voussoirs in the model, being 4 in., will afford a scale to ascertain the proportionate width of the bridge, which is 16 ft.; and the span of the arch in the model is 36 in., which equals 144 ft. in the bridge, which is nearly right.

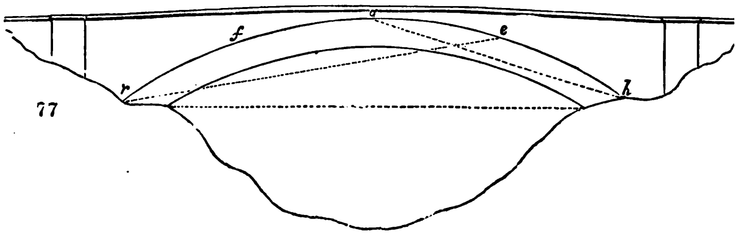
It will be seen, by looking back to figs. 11 and 12, Essay II. p. 16, which are similar segments to the bridge under consideration, that the haunches, or the additional weight contained in *c k b*, strengthened rather than weakened the arch, particularly when added to both sides, as in the latter figure of the two above referred to. But it must be observed, that the depth of the voussoirs at the crown in those figures is great, which, it may be presumed,

was not the case in the bridge of Mr. Edwards's construction; consequently, this deficiency was the cause of the downfall of the first bridge, as exemplified in *Ex.* 12, 13, and 14, (p. 20, 21.)

In following up the experiments with the model, the haunch at *e* (fig. 76) was built up to nearly a level with the crown; when at the height of *b*, over *e*, the arch carried 12 lb. Upon placing similar masonry on the opposite side, the arch, at the point *b*, carried more than 24 lb; thus proving again, as was the case in the experiments above alluded to, that masonry at the haunches, when the crown is of sufficient thickness, adds strength to the structure.

Again, an arch (fig. 77) was made of the segment of a circle the radius of which equalled its span, or 140 ft.;

77



having the voussoirs 10 ft. deep as before, in fig. 76. This arch carried, at *e*, 16 lb well. Now, on inspecting these two elevations, the dotted line *a h*, fig. 77, will be found to be quite within the voussoir; but this is not the case with the line *a h*, fig. 76; also, the dotted line *e r* in fig. 77 is considerably nearer the intrados than *e r* in fig. 76; therefore proportionally the stronger: or fig. 77 would have required less depth of voussoirs or masonry at the crown; therefore, that it has two advantages, namely, greater strength, and an easy ascent for carriages, which Mr. Edwards found out afterwards.

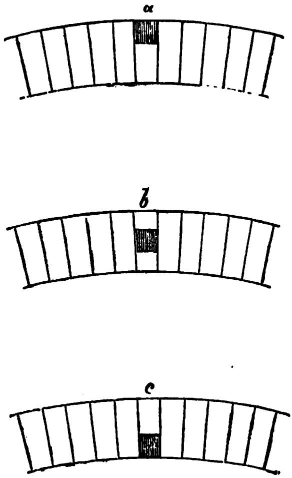
Since much has been said respecting the depth of vous-

soirs, a trial was made to ascertain what would be the result on substituting a voussoir of 4 ft. in depth in the room of one of 10 ft. This was carried into effect in the model by exchanging the key or crown voussoir for one of only 1 in. in depth, which is equivalent to 4 ft. The diagram fig. 78 represents crown portions of the arch, having the dark voussoir to represent the small one, which was first placed at *a*; then in the middle, as in *b*; and, lastly, at the bottom, as in *c*.

On putting the weights at *e*, on the arch fig. 76, the results were as follow: — With the small voussoir in the position shown at *a*, fig. 78, the arch carried 2 lb; when the same voussoir was placed as shown at *b*, the arch carried 4 lb; and when in the position shown at *c*, 8 lb was the weight the arch sustained.

When the weights were placed at *e*, fig. 77, the results were thus: — The small voussoir being at *a*, the arch carried 3 lb; when at *b*, 6 lb; and in the position shown at *c*, 12 lb.

78



Now, on removing the weights to the crown over *a*, the results of both arches (figs. 76 and 77) were inversely of those given when the weights were at *e*, by the arch carrying the most when the small voussoir was in the position shown at *a*; and the least when the same voussoir was placed as shown at *c*.

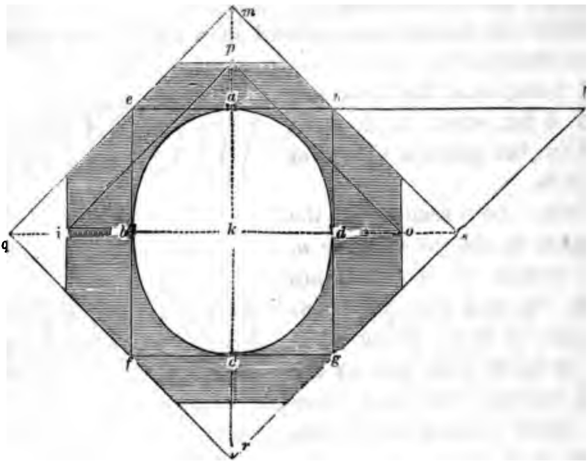
We have here a strong proof of the propriety of the key-stone of arches fitting closely at all parts of the adjoining voussoirs.

Of the Tunnel.—The objects for which tunnels are con-

structed are usually for the purpose of thoroughfares underground, as through hills, &c.; for man alone, for carriages and horses, for canals, and for railroads.

The figure of a man, and his loads, at once determine the requisite form; namely, the oval or elliptic. It is well known that an egg will sustain, without breaking, very great force of pressure when placed endways between the hands: yet the shell is particularly thin. From this fact it appears, that nature's form of the egg is the form best adapted to a tunnel. The dimensions of an egg are $2\frac{1}{8}$ in. for the greater axis, and $1\frac{5}{8}$ in. for the smaller axis; or, the axis major is to the axis minor as 17 is to 13. The diagram fig. 79 is described after these proportions.

79



Having laid down the axis major $(a\ c)$ at $2\frac{1}{8}$ in. and the axis minor $(b\ d)$ at $1\frac{5}{8}$, the ellipse $(a\ b\ c\ d)$ was described by taking $\frac{2}{3}$ of the axis major for the radius of the sides, and the remaining $\frac{1}{3}$ for the radius of the ends. These two segments of circles coincided exactly, which was not the case with segments of dissimilar radii.

Let $a\,b\,c\,d$ be the ellipse described from the centres of two circles, instead of two foci, making the dimensions proportionate to the natural size of the egg selected; then $a\,c$ is the axis major, and $b\,d$, bisecting $a\,c$ at right angles at k, is the axis minor. At the points b and d, draw the straight lines $e\,f$ and $h\,g$ parallel to $a\,c$; and at the points a and c, draw the straight lines $e\,h$ and $f\,g$ parallel to $b\,d$. Produce $a\,c$ indefinitely both ways, and let $a\,m$ equal $a\,e$ or $a\,h$; and $c\,r$ equal $c\,f$ or $c\,g$. Join $e\,m$, $m\,h$, $f\,r$ and $r\,g$. Produce, likewise, $b\,d$ indefinitely both ways, and let $d\,n$ equal $d\,h$ or $d\,g$; and $b\,q$ equal $b\,f$ or $b\,e$: join $h\,n$, $n\,g$, $f\,q$, and $q\,e$. Now, in the triangle $a\,e\,m$, the angle $a\,e\,m$ equals the angle $a\,m\,e$: and the angle $e\,a\,m$ is a right angle; therefore, the angle $a\,e\,m$ equals 45°. In like manner, it may be shown that the several angles $a\,h\,m$, $d\,h\,n$, and $d\,g\,n$ equal 45°: also, the same may be shown in the triangles $g\,r\,f$ and $f\,q\,e$.

In experiment Tenth (p. 17) it is proved that masonry forms a natural arch at the angle of 45°, and will carry a heavy weight on m, fig. 14 (p. 18), because of the straight line $m\,a$.

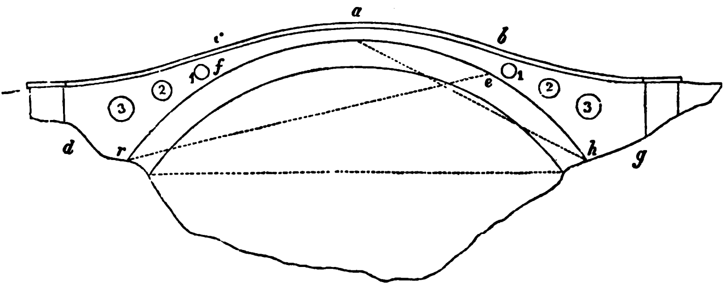
If this be the case with masonry, the law with regard to the pressure of solid earth must be similar; and the weight to be borne on the arch at a, fig. 79, equals the triangle $e\,m\,h$ in perpendicular pressure. As respects lateral pressure, it is known that a bank of earth will just support itself when inclined at an angle of 45°. Produce $e\,h$ and $g\,n$ until they meet l. Let $g\,n\,l$ be a plane inclined 45°; and let $g\,h\,l$ be a mass of earth resting upon this inclined plane, and, consequently, pressing against $h\,g$. If the straight line $l\,g$ represent the force of this body of earth, it may be resolved into the two straight lines $l\,h$ and $h\,g$ (see *Wood's Mechanics*, Prop. II.): but $h\,g$ is parallel to the side; therefore, $l\,h$ is the force which alone acts against the side. In the two triangles $h\,g\,n$ and $h\,l\,n$, it may be easily proved that $l\,h$ equals $h\,g$; and the triangle $h\,g\,n$

1 ton 12 cwt.; or, all together, under 6 tons. Let it be possible for a load to go over the bridge equalling 12 tons; this load would take up one third of the width of the road-way. Now, it has been shown that one third of the bridge will carry 360 tons, or 30 times 12 tons.

With the view of ascertaining what weight the bridge would carry without opening the joint at the keystone, a vessel of paper was suspended in the angle of the joint, being inserted $\frac{1}{2}$ in. up the joint on the outside, and 1 in. along the joint underneath. The arch carried 6 lb on the crown; but a greater weight caused the paper to fall down by the opening of the joint underneath. Now, 6 lb multiplied by 20 (the number of tons which 1 lb in the model represents) gives 120 tons; therefore proving most satisfactorily that the strength of this bridge is many times greater than the weight of any load which can possibly be drawn over it; and this, too, independently of the two banks, which act as buttresses.

Ponty Prydd Bridge.—This bridge, in Glamorganshire, represented by fig. 76, which was designed and constructed by an uneducated architect (William Edwards), is of one arch,

76



extending 140 ft. in span; the rise, or altitude, being 35 ft. The arch forms the segment of a circle, the diameter of which is 170 ft. It was completed in the year 1755. (See Malkin's *South Wales.*)

The engraving is correct in the proportions of span and rise of this famous arch, having *d* and *g*, the buttresses, of living rock, and therefore immovable. The depth of the voussoirs, or the thickness of the masonry of the bridge at the crown (*a*), is not given by Mr. Malkin. This arch was put to the test of experiment by a model made of wooden voussoirs. The scale being of a quarter of an inch to a foot, allowed 10 ft. for the depth of the voussoirs, which dimension is adopted in the elevation (fig. 76). Now, the arch, so constructed, carried 8 lb placed on the voussoirs at *e*: more than this weight caused the opposite part of the arch to fly up at *f*. According to the scale of the model, 8 lb equals 540 tons.

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It will be seen, by looking back to figs. 11 and 12, Essay II. p. 16, which are similar segments to the bridge under consideration, that the haunches, or the additional weight contained in *c k b*, strengthened rather than weakened the arch, particularly when added to both sides, as in the latter figure of the two above referred to. But it must be observed, that the depth of the voussoirs at the crown in those figures is great, which, it may be presumed,

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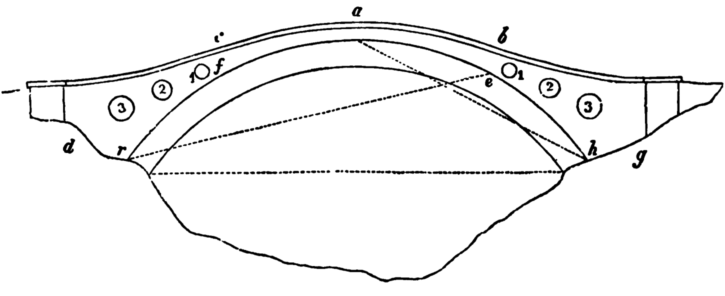

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proper width. The whole width, then, would balance with nearly 340 tons, the pier having no counteracting arch or buttress. But with abutting arches, the model carried 9 lb, when composed of voussoirs only; consequently, when the masonry is completed to form the horizontal road, the arches and piers will carry very considerably more than 9 lb: indeed, 18 lb, or 3060 tons, may be sustained on the crown of any of the arches. This weight is sufficient to prove the strength and stability of this fine structure for the safe passage over of any loads, whenever it may be erected.

The great difference between Rochester Old Bridge and the proposed new one, as planned by Sir Robert Smirke, is in the thickness of the piers of the former bridge to those of the latter, when the spans of the arches of both are considered; the one being three fourths of the span, the other one sixth.

Waterloo Bridge.—This masterpiece of bridges, the work of Mr. Rennie, was finished and opened in the year 1817. It consists of nine cycloidal arches, each of 120 ft. span, with a horizontal roadway.

82

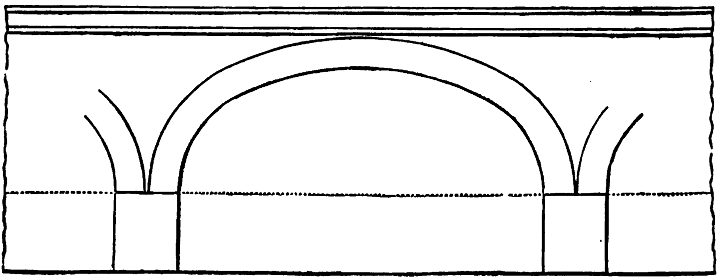


Fig. 82 exhibits one arch and two piers. The span of the arch is here drawn, for convenience, more after the elliptic form than that of the cycloid. The thickness of the piers

is 20 ft., which is one sixth of the span of the arch. The width of the piers is from 46 ft. to 50 ft., and their height is assumed to be 25 ft. The model employed for experiment was on the scale of 1 in. to 5 ft.; and, being 4 in. wide, it equalled two fifths of the width of the bridge.

The model arch, when composed of voussoirs only, balanced on piers 4 in. thick and 5 in. high; that is, on piers 20 ft. thick and 25 ft. high. When the arch had the haunches and spaces over the piers raised with wooden bricks to the level of the crown, it balanced with $2\frac{1}{2}$ lb placed on the crown. Another arch, of equal and similar dimensions, being placed with one foot on the same pier as the first, which then became a middle pier, the two outside piers being made immovable, and both arches composed of voussoirs only, either arch balanced under the weight of 5 lb.

The scale of the model being 1 in. to 5 ft., there are, in proportion, 125 cubic feet in 1 cubic inch; and, since 20 cubic inches of the model equal the weight of half a pound, then 2500 cubic feet will be in proportion to the same weight. Now, 15 cubic feet of stone equals 1 ton; therefore, there are, in proportion, 166 tons in half a pound; and in $2\frac{1}{2}$ lb 830 tons; which latter is the weight the arch and piers will balance under, when it has masonry to the level of the crown. Let it be remembered that this $2\frac{1}{2}$ lb is supported by only two fifths of the width of the arch, which latter would, if of the full width, carry 2075 tons. With another arch abutting against the first, either of them will then balance with just double of the above weight when composed of voussoirs only, or 4150 tons; consequently, with masonry to complete the bridge, either of the arches would sustain considerably more. From this it is apparent that 6, 20, or even 50, tons would have no effect towards disturbing the equilibrium of this superb fabric.

On comparing Rochester New Bridge with Waterloo Bridge, there appears this difference: the former balances

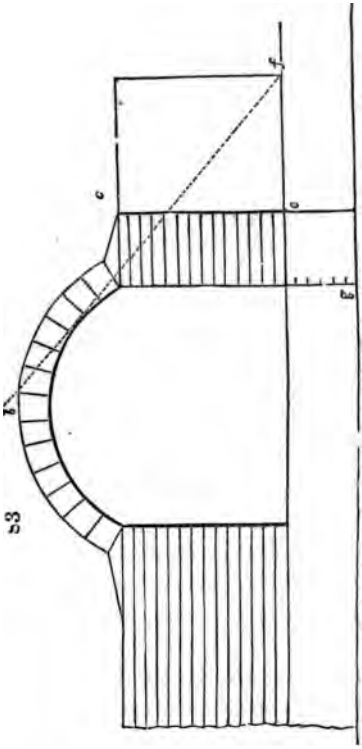
on a pier much less in height than the latter, when a single arch of both are considered; but, when the arches have others abutting on them, the strength of the former becomes conspicuous, on allowing to both the same width. This is explained by many of the experiments in the foregoing essays, simply by the nearer approach of the straight line.

Whilst constructing the Rochester New Bridge model, a difficulty was experienced in preventing the arch, composed of voussoirs only, from forcing off the top courses of the piers, which was not the case with the cycloidal arch.

The architects of a few centuries back, and those of the present day, differ considerably in the proportions which each employed in the formation of bridges; the arches of the former being small, with very large piers; whereas those of the latter are of very large span, with proportionally small piers. The modern architects, it must be admitted, have immense advantages, which were not available to their predecessors; not only by the experience they derive from the labours of those gone before them, but from the great progress which both art and science have made, comparatively within these few years. The principal advantages have been, and are, that stone of any dimensions may be procured for voussoirs, and the steam-engine may be used to clear out the water whilst forming foundations in rivers.

It will be seen by the sequel that the constructors of Rochester Old Bridge and of London Old Bridge were correct, as far as circumstances went. For example, let the diagram fig. 83 represent arch 3 of Rochester Old Bridge, being 30 ft. span, 9 ft. rise, and forming the segment of a circle. Now, this segment corresponds with the segmental arch 3, but is composed of thirteen voussoirs. It has been observed that the arch composed of twelve voussoirs just balances on piers 4 in. thick, and 8 in. high: and an arch composed of thirteen voussoirs will balance on a similar pier; while, on increasing the thickness of the piers to 6 in.,

the same arch is found by experiment to balance on them when raised to 20 in. high; that is, from *g* up to *c* in the diagram fig. 83.



83

It will be seen, when treating of the arches and piers in churches, in a subsequent essay, that the proportion of one sixth regulates the dimensions of the piers as to their diameter and height. The truth of this law is confirmed in the above instance; since, having increased the base of 4 in. to 6 in. in thickness, the additional 2 in., being multiplied by 6 in., give 12 in.; which, when added to 8 in., the former balancing height, equal 20 in., the latter balancing

height. Let 6 in., or six courses, be taken from the pier *c g*, leaving the height *c e*: this, according to the same law, equals 1 in. of increase of thickness to the pier; and the scale of the model being 1 in. to $1\frac{1}{2}$ ft., *e c* will be 21 ft. high, which corresponds nearly with the assumed height of the pier of Rochester New Bridge.

On putting to experiment this thirteenth voussoir arch, with a pier 14 in. in height, they balanced with three quarters of a pound on the crown of the arch; and, being of the same scale of model as employed for Rochester Bridge, will equal $23\frac{1}{2}\ \frac{1}{8}$ tons on the whole width. With another equal and similar arch abutting against the first, either arch balanced with 6 lb, which will equal, for the reason given above, 189 tons. Let this weight be compared with the weight which the arch 3 of Rochester Old Bridge will carry, having the piers 22 ft. in thickness; likewise, let it be compared with Rochester New Bridge under the same circumstances of voussoirs only:—

With a single arch and pier, they balanced as under:—

The thirteenth voussoir arch and pier balanced with $26\frac{1}{2}\ \frac{1}{8}$ tons.

Rochester Old Bridge balanced with 441 tons.

Rochester New Bridge just balanced.

With another arch abutting, the following were the results:—

The thirteen voussoir arch, &c., balanced with 189 tons.

Rochester Old Bridge balanced with 693 tons.

Rochester New Bridge balanced with 3060 tons.

From these results, it appears that the pier *c e* (fig. 83) is not of sufficient thickness to support the necessary weight of laden carriages, without endangering the equilibrium of the bridge; yet the pier is nearly one third of the span.

On looking back to the fourth experiment in Essay IV., it will be seen that strength can be given to a fabric by *raising* the structure with masonry over the piers and *crown of the arch*; and if this were carried up in fig. 83,

the arch would sustain a great weight. But then what a mass of masonry would be required; adding not only to the expense, but proving an immense load on the piers, which are situated upon an uncertain foundation, besides raising the roadway to a most inconvenient height?

It appears, then, from this, that there was no other alternative with the ancient builders but to increase the thickness of the piers, as *c f*, taking the never-failing straight line *b f* to regulate the dimensions.

Enough has been shown, to prove that the proportion between the thickness of a pier and the span of its arch is not regulated by each other, for structures destined to have great and uncertain weights to pass over them. It is the proportion of the mass of matter of the arch, to the weight that is to pass over it, which must regulate the whole: for instance, an arch of only 30 ft. span cannot contain the same weight of materials as an arch of 100 ft.; consequently, a weight of only 6 tons would have proportionally greater effect over the equilibrium of the 30 ft. span arch than it would have over the arch of 100 ft. span, allowing the same width of roadway to each.

It is this, and this only, which must ever require thick piers for small arches, and which will allow of one sixth of the span of large arches for the thickness of their piers; at the same time, never omitting to keep within, or, rather, not to exceed the balancing height of a voussoir arch, on its pier. This, under all circumstances of bridge architecture, ought to be the limit.

Having proceeded thus far with bridges, a list is subjoined, showing the relative weights sustained by the bridges which have been treated of.

First, of single arch bridges:—

Loose Bridge, with masonry level over the crown and piers, carried 1134 tons.

Ponty Prydd Bridge, with voussoirs only, and piers immovable, carried 1360 tons.

Secondly, of bridges of more than one arch:—

Rochester Old Bridge, with voussoirs only, employing one arch and two piers, carried 441 tons.

The same bridge, with another arch abutting to the first, carried 693 tons.

Rochester New Bridge, with voussoirs only, employing one arch and two piers, just balanced, or carried nothing.

The same bridge, with another arch abutting, carried 3060 tons.

Waterloo Bridge, with voussoirs only, employing one arch and two piers, just balanced, or carried nothing.

The same bridge, with another arch abutting, carried 4150 tons.

When two arches were placed abutting each other, the middle pier only was movable: the end piers were fixed.

ESSAY VIII.

RELATIVE TO THE ARCHITECTURE OF SMALL CHURCHES.

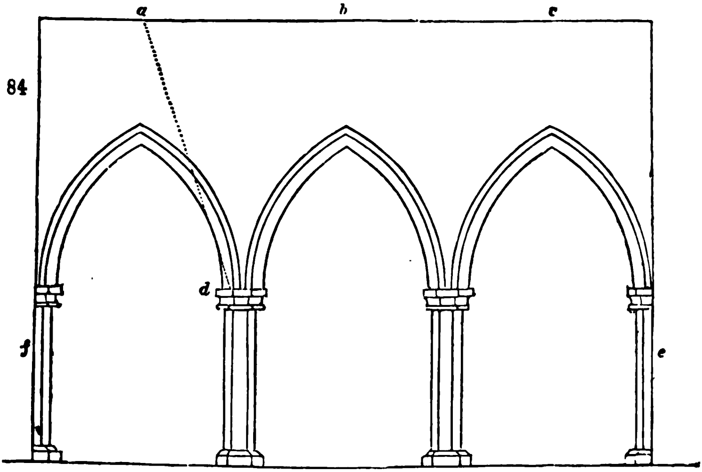
Hartlip Church, in Kent.—The engraving fig. 84, represents three arches, and their piers or pillars, which compose one side of the body of this church.

The span between the piers is 10 ft. The height of the piers is also 10 ft. The shaft of the piers is 8 ft. The diameter of the piers is 20 in.; and the form is octagonal. The thickness of the wall on the arches is 2 ft. 2 in. The masonry above the arches is 7 ft. high.

Now, in 10 ft. there are 120 in.: this number, divided by 20, the diameter of the pillars, gives 6; that is to say, the diameter of the piers is just one sixth of the span of the arch. On turning to fig. 56, it will be seen that the *pointed arch*, composed of voussoirs only, just balances on

nearly equal dimensions of span and pier; having the diameter of the pier one sixth of the span. Again, in the experiment fig. 50, it is shown that, when the masonry is carried up to *a b*, the arch will carry double the weight it supported without the masonry. Now, the rise of this arch is 8½ in., the span being 10 in., and the masonry above the rise 3½ in.

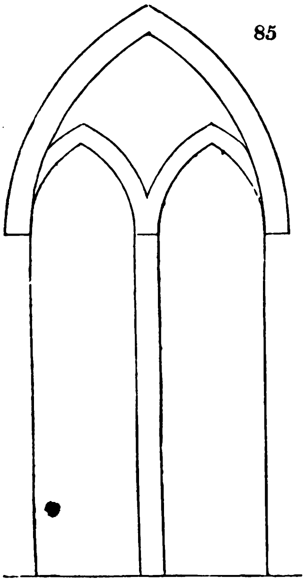
84



In the drawing of the church (fig. 84), the masonry above the rise is 7 ft., which equals the height of the fourteenth course in the last experiment referred to. From this, it is evident that the height of the masonry has added at least six times to the stability of each arch and pier above the balancing point, that point being called 1, and the strength of the mortar not being taken into consideration; therefore proving the structure to be amply secure of itself. But it is further strengthened by having the tower as a buttress at one end (*e*), and cross walls, &c., at the other end (*f*). Being thus circumstanced, any one of the arches will carry, at the points *a b*, and c, 60 lb.; which

equals forty times the weight of one of the piers, and, therefore, proves the durability of this part of the church for ages.

The point *a* is perpendicularly over the crown of the arch beneath; and a straight line may be drawn from that point to the pier, just touching the intrados of the arch, as represented by the dotted line *a d*.



85

Windows. In the south-west window of Hartlip Church, represented by fig. 85, the plan and proportions are as follows:—

The span, or opening, is 20 in. The thickness of the middle jamb is 5 in. The height of the opening to the springing of the arch is 66 in. Now, if each of the above sums be divided by 5, the dimensions of the jamb, the proportions will be thus:—Opening, 4; jamb, 1; height, 13.

On putting the above jamb to experiment, with the arch of the opening resting upon it, and the springing of the arch quite coinciding with the line of the jamb beneath, as represented in the engraving, the arch just balanced firmly on the jamb when it was exactly half the height of the window jamb; consequently, the jamb of the window is exactly double the balancing height of the arch. The jamb is one fourth of the span; and its height is three times the span, and the thickness of the span over.

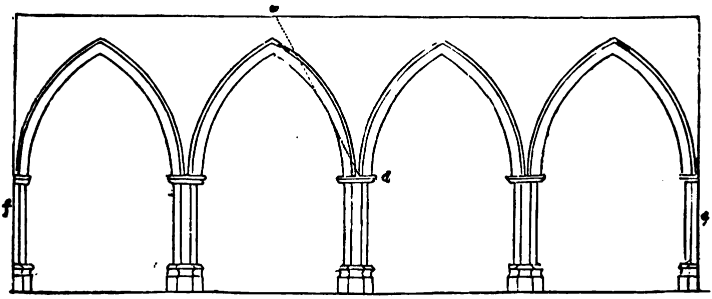
Another window of this church was measured, being the *east window of the* south chancel. The dimensions were as

follows: — span, 2 ft., or 24 in. Thickness of the jamb, nearly 6 in. Height of the jamb, $6\frac{1}{2}$ ft., or 78 in. Now, these sums being divided by the thickness of the jamb, will give the following: — Span, 4; jamb, 1; height, 13; being the same as the former window.

In all the beautiful tracery-work above the jambs of the windows of churches which I have examined, I found that the straight line principle was carefully attended to.

Newington Church, near Sittingbourne. — The engraving fig. 86 represents one side of this church: *e* is the tower wall, and *f*, the cross walls, &c.

86



The span between the piers is 13 ft. The height of the piers, 10 ft. The shaft of each pier, which is octagonal, is 7 ft. high. The diameter of the shaft is 24 in. The thickness of the wall on the arches is 28 in. The masonry above the arches is 3 ft high. In 13 ft. there are 156 in., which, divided by 24 in., gives $6\frac{1}{2}$ in., the proportion of the diameter of each pier to the span of the arch: but the true diameter, according to Ex. 56., should be one sixth of the span, or 26 in.: the height, however, of the piers is only 10 ft., instead of 13 ft.

While the proportion of one sixth, in the above-mentioned experiment, gives the balancing point, the same is the case between the diameter of the pier and its height; for 1 in.

in the diameter equals 6 in. in height of the pier, or 2 in. to 1 ft.

Now, in Newington Church, the piers are 2 in. within the true diameter, which would require their height to be shortened 1 ft.: but they are shortened 3 ft.; therefore the strength may be estimated as 2 ft. within the balancing point, as given in the above experiment; and which, by another experiment, nearly equals one third of the weight of one of the piers.

The height of the masonry above the arches is 3 ft. In the experiment fig. 50, it is shown that, when the masonry is completed up to the dotted line *a b*, the strength of the fabric is increased double; and the height of this dotted line corresponds very closely with the masonry of this church. If, therefore, any one of these arches, composed only of voussoirs, and placed on these piers, will carry one third of the weight of one of the piers, it will, with the masonry above, as represented in the engraving, carry or balance with two thirds of the weight of one of the piers. Now, these arches and piers, being placed abutting against each other, and having the tower at one end, and stout walls with cross arches at the other, are evidently secured against falling.

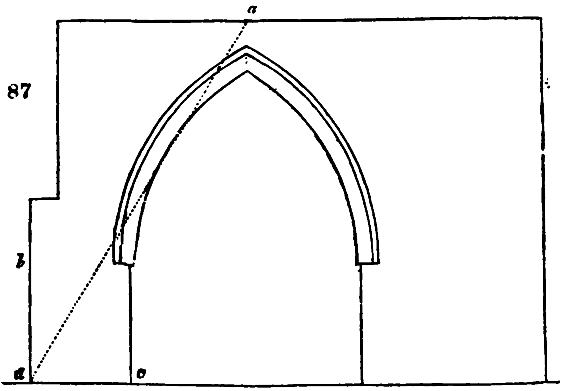
The dotted straight line *a d*, just touching the intrados, falls on the pier at a distance without its centre; whereas, in Hartlip Church, the dotted straight line *a d* falls on the top of the pier at a distance within the centre.

Fig. 87 represents the main cross arch, over the pulpit, and leading to the communion table, of Newington Church. The span of the arch is 15 ft. The height of the small pier *b c* is 8 ft. The diameter, or depth, of this pier is 6½ ft. The thickness is the same as the masonry on the arch. The masonry above the arch is 3 ft. high.

In 15 ft. there are 180 in.; and one sixth of this gives 30 in. for the true diameter of the pier: but the depth of

the pier *b c* equals 78 in. Or, the true diameter to the depth of this pier is as 1 to $2\frac{1}{2}$.

87

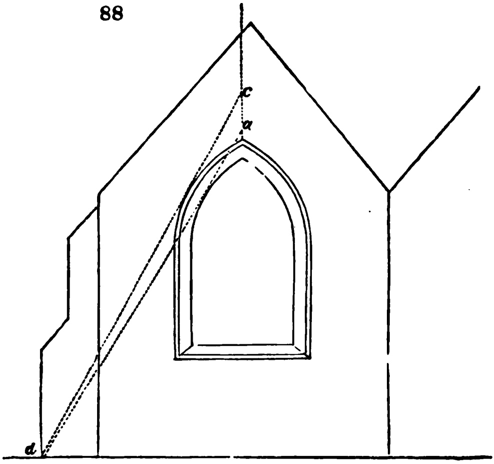


In the experiment fig. 21, it may be seen that twice the depth of a pier adds four times to the strength. Again, in the experiment fig. 56, when the pier is reduced in its height to one half, the arch and pier will carry twice the weight of the pier. A straight line may also be drawn from *a* to *d* (fig. 87), which nearly falls within the voussoirs. Moreover, the pier *b c* is farther strengthened by a cross wall. All these circumstances being considered, this fabric is capable of supporting a great weight on *a*. The test of experiment proved the arch and pier to stand firm under a weight of 60 lb placed at *a*; consequently, they would carry more: but this was a sufficient test of strength; and this weight of 60 lb equalled twenty times the weight of the small pier.

Fig. 88 represents an eastern window of Newington Church. The span of the arch is 8 ft. The height of the window to the spring of the arch is $7\frac{1}{2}$ ft. The height of the masonry from the ground to the bottom of the window is 8 ft. The walls on each side of the window are $6\frac{1}{2}$ ft. The depth of the buttress is 4 ft.

The masonry of this window exhibits the straight line *a d* just touching the intrados, and the straight line *c d* within the masonry; consequently, this fabric will support almost any weight on *c*, and, therefore, will never fall of itself. Its present appearance confirms this, since it looks as strong as when first erected.

88



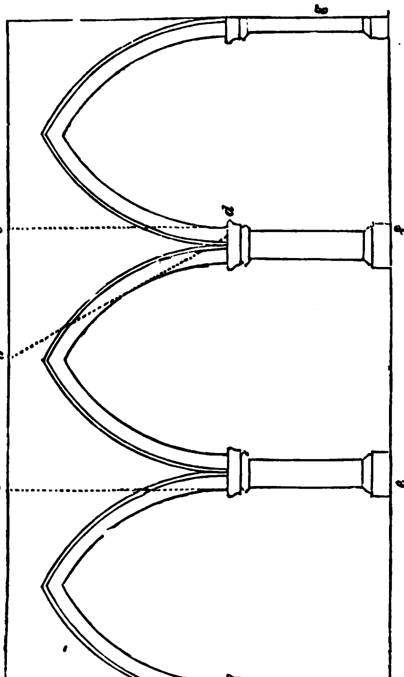
Sittingbourne Church.—The engraving fig. 89 represents one side of this church: *g* is the tower wall; and *h* the cross wall, &c. The span of the arch is 14 ft. 3 in. The height of the piers, 11 ft. 2 in. The shaft of the pier 8 ft. 8 in. The diameter of each pier, 24 in. The thickness of the masonry on the arehes, 2 ft. 9 in. The height of the masonry above the arches, 4 ft. The piers are, in form, circular and octagonal alternately.

In 14 ft. 3 in. there are 171 in., which, divided by 6, gives $28\frac{1}{2}$ in. for the true diameter of the pier: but the pier is only 24 in. in diameter; therefore it is $4\frac{1}{2}$ in. within the balancing point.

It has been before shown, in the description of Newington Church, that every 2 in. less in the diameter of a pier re-

quires a reduction in its height of 1 ft., to preserve the equilibrium. In this instance, then, as the diameter of the pier is $4\frac{1}{2}$ in. within the one sixth of the span, the reduction in the height of the pier must be 2 ft. 3 in. Now, this

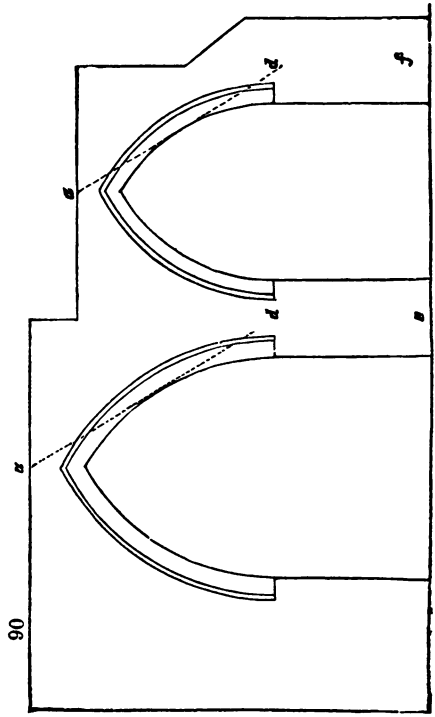
89



sum, taken from the span of 14 ft. 3 in., makes the true height of the pier to be 12 ft.: but the height of the pier is 11 ft. 2 in.; therefore it is 10 in. within the balancing point.

On submitting one arch and pier of this church to the test of experiment, the results were, that, with voussoirs only, the arch and pier carried three eighths of a pound on

the crown. When masonry was erected on the arch, equal to the proportions represented in the engraving, and as contained within the dotted lines and the piers *b e*, *f c*, the arch and piers carried on *a* $2\frac{1}{2}$ lb. Now, the weight of one



pier equals $1\frac{3}{8}$ lb; consequently, the arch will carry, or balance with, nearly twice the weight of one pier. These arches, being three in number, are, together with their piers, placed between the tower wall at one end, and a cross wall, &c., at the other, and are thus sufficiently secured against falling.

The effects of the pedestal and capital, which project be-

yond, and exceed the diameter of, the shaft of each pier, are not taken into the calculation in any of the churches here considered. They, however, by their increased base and height, shorten each pier a little, and consequently, contribute to the stability of the whole structure. The dotted line *a d* falls very nearly on the outside edge of the pier.

Fig. 90 represents two arches of this church. The larger arch separates the body of the church from the altar chancel.

Relative to the larger Arch. The span between the piers is 16 ft. 2 in. The height of the pier *e* is 11 ft. 2 in. The diameter, or depth, of the pier *e* is 5 ft. 9 in. The thickness of the wall on the arch is 2 ft. 9 in. The masonry above the arch is 3 ft. 6 in.

In 16 ft. 2 in. there are 194 in.; which, divided by 6, gives $32\frac{1}{3}$ in., or 2 ft. 8 in., for the true diameter: but the depth, or diameter, of the pier *e* is 5 ft. 9 in.; it is therefore twice the true diameter, and 5 in. over. The height of the pier *e* is 11 ft. 2 in.; therefore shorter than the span by 5 ft.

We have, then, in these two instances of the diameter and height of the pier, great increase of strength to support the arch beyond the balancing point.

Under the test of experiment, the arch composed of voussoirs only, and the pier *e*, made, for the sake of convenience, 6 in. or 6 ft. through, instead of 5 ft. 9 in., carried on the crown 14 lb. Now, the pier employed weighed 4 lb.; therefore the arch balanced with three and half times the weight of the pier *e*. On completing the masonry, to correspond with the drawing, the arch carried 56 lb: this weight equals fourteen times the weight of the pier *e*.

Relative to the small Arch. The span of the arch is 12 ft. 6 in. The height of the pier *f* is 11 ft. 2 in. The diameter, or depth, of the pier is 6 ft. 3 in. The thickness of wall, and the height of the masonry above the arch, are the same as in the larger arch.

In this span there are 150 in., which, divided by 6, gives 25 in. for the true diameter: but the pier *f* is 75 in. through, or just three times the true balancing diameter. The height of the pier *f* is 11 ft. 2 in.: it is therefore 16 in. shorter than the balancing height. Here, again, considerable strength is gained beyond the balancing point, which is proved by the following experiments: —

With the arch constructed of voussoirs only, and the pier the same as with the larger arch, it carried on the crown 18 lb, or four and a half times the weight of the pier of 4 lb: and, with masonry above, as in the engraving, the arch stood firmly under 64 lb: therefore it would have carried more, particularly as the experimental pier was 3 in. within the diameter of the pier *f*.

Having proceeded thus far, let the effects of these two arches resting upon the same pier *e*, be now taken into consideration.

It has been shown that the pier *e* is itself of sufficient firmness to carry the large arch and masonry. It is, however, assisted in its stability against the thrust of this arch by the counteracting thrust of the small arch; consequently, it is ably secured against falling, or being overturned, under common circumstances. And, with respect to the stability of the small arch, the pier *f* has been shown, by experiment, to be of ample dimensions to insure its stability.

Again, both arches have their piers further strengthened by the cross arches and walls of the church, which abut against them at right angles to the thrust of these arches.

The dotted straight line *a d*, in the large arch, falls at the point *d*, on the centre of the pier: and, in the small arch, the dotted line *a d* is within the centre of the pier, at the point *d*.

When treating of churches, the arches and piers contained in them were placed abutting each other in straight lines. Now, in some chapels, and the under crofts of cathe-

drals, the arches with their piers are found running in parallel series, and intersecting each other at right angles, in the line of every pier; the object being the formation of a basis for floors above.

ESSAY IX.

RELATIVE TO THE ARCHITECTURE OF SMALL CHURCHES AND CATHEDRALS.

The Lady Chapel of St. Saviour's Church, Southwark. — Fig. 91 represents one side of this beautiful building, which shows a specimen of a series of cross arches, and pillars or piers. The particulars of the dimensions are as follows:—

The span between the piers is 13 ft. The height of the piers is 11 ft. 6 in. The height of the shaft is 10 ft. The diameter of each pier is 23½ in.; and their horizontal section is something of the form shown at *b*. The height of the masonry over the crown of each arch is 2 ft.

Now, in 13 ft. there are 156 in., which, divided by 6, gives 26 in. for the diameter of each pillar: but the diameter is 23½ in., therefore 2½ in. too small; consequently, each pier requires the reduction of 1 ft. 3 in. in the height, taken from the dimensions of the span; thus leaving 11 ft. 9 in. for the balancing height of the piers: but the piers are 11 ft. 6 in. As their proportions approach so near to each other, it is probable that a mistake might have been made in the measurement of the diameter, by having allowed a trifle too much. The above proportions exactly coincide with those required for arches and piers running in a single series, as in Hartlip Church.

In the Lady Chapel, it has been stated that several serie of arches and piers cross each other at right angles; there-

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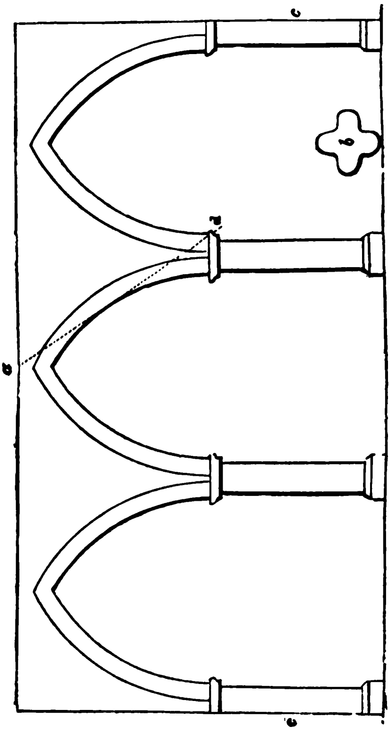
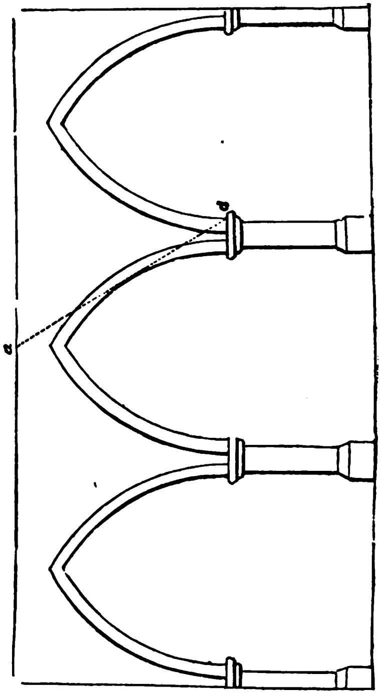


fore, according to the experiment (fig. 65 p. 66), they w thus circumstanced, carry double the weight of a sin series.

The architects were fully aware of this, and availed the selves of it to give lightness and beauty to the structu which they have admirably accomplished by the conca section up the four sides of every pillar.

The dotted line *a d* terminates at *d* on the outer edge *the pillar*: *c c* are the walls.

Rochester Cathedral. — Fig. 92 shows a part of the crypt under the choir of this cathedral, consisting of a series of



92

arches and piers crossing each other at right angles. The particulars of the dimensions are as follows: —

The span between the piers is 8 ft. 7 in. The height of the piers is 6 ft. 1 in. The height of the shaft is 4 ft. The diameter of each pier is 12 in.; and their form is alternately circular and octagonal, and not of one solid piece of stone. The height of the masonry above the arches is 2 ft.

In 8 ft. 7 in. there are 103 in., which, divided by 6, gives 17 in. for the true diameter: but the diameter of the piers is 12 in., and, therefore, 5 in. too small; consequently, each

pier requires a reduction in the height from 8 ft. 7. in. to 6 ft. 1 in., to be in the balancing proportion to the span. Now, the piers are just 6 ft. 1 in. in height; therefore, they are strictly of the true balancing proportion to the span of the arches. The experiment shown by fig. 65 (p. 66), proves the double strength of these cross arches and piers of the under croft.

The dotted line *a d* terminates at *d*, on the outer edge of the pier, the same as in the Lady Chapel.

The Nave of Rochester Cathedral. Relative to the Norman and Saxon arches and pillars near the tower.—Fig. 93 shows the arches and piers: the superstructure is not represented, and some of the Saxon arches are omitted.

The particulars of the pointed arches and their pillars are as follows: — The span between the piers is 8 ft. 9 in. The height of the piers is 19 ft. 6 in. The height of the shaft is 17 ft. The diameter of the piers, which are circular, is 5 ft. The height of the masonry above the arches is 7 ft.

In 8 ft. 9 in. there are 105 in., which, divided by 6, gives $17\frac{1}{2}$ in. for the true diameter of the piers: their diameter, however, is 5 ft. or 60 in. Now, $17\frac{1}{2}$ taken from 60 leaves $42\frac{1}{2}$; and, since 2 in. in diameter equals 1 ft. in height, to preserve the balancing proportion, the $42\frac{1}{2}$ in. will give 21 ft. 1 in. more to the height of the piers above the span. Or 8 ft. 9 in. added to 21 ft. 1 in. equals 29 ft. 10. in. for the balancing height: but the height of the pier is 19 ft. 6 in.; therefore, these may be allowed to be within the balancing dimensions by one third of their true height.

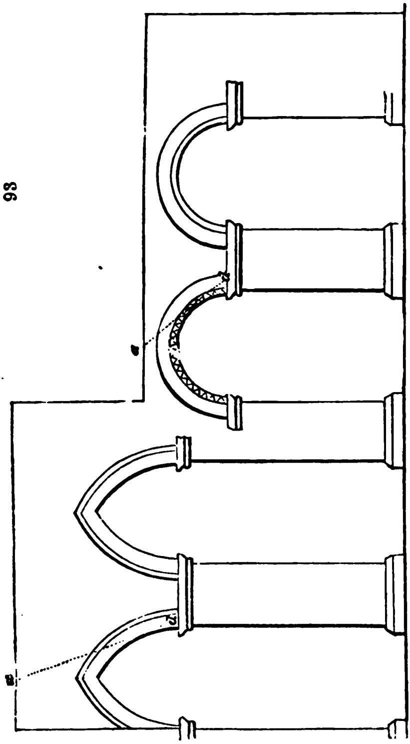
These arches and piers were submitted to experiment by a model; and the result was, that a single arch and pier balanced under one third of the weight of its pier, the masonry above the arch being entirely omitted.

The dotted line *a d* falls on the inside edge of the pier at the point *d*.

The particulars of the Saxon arches and piers (fig. 93) are as follows: — The span between the piers is 9 ft. 6 in.

The height of the piers is 15 ft. 3 in. The height of the shaft is 13 ft. The diameter of the piers, which are circu-

93



lar, is 5 ft. The height of the masonry above the arches is $2\frac{1}{2}$ ft.

In 9 ft. 6 in. there are 114 in., which, divided by 6, gives 19 in. for the true diameter of the piers: but the diameter of these piers is 5 ft. or 60 in. Now, 19 taken from 60 leaves 41 in., which, as it has been before observed, equals $20\frac{1}{2}$ ft., and, when added to the span of 9 ft. 6 in., makes the balancing height 30 ft.

According to the experiments relative to figs 56 and 57 (pp. 54, 55), the pillar of fig. 57 is one fourth less than the pillar of fig. 56; therefore, the pillar of the Saxon arch should be reduced from 30 ft. to 22½ ft. high. But these pillars are 15 ft. 3 in. high; consequently, they are one third less than their true height, and corresponding, in this respect, with the Norman pillars.

When these arches and piers were submitted to the test of experiment, a single arch and pier balanced under the weight of nearly one half of its pier, the masonry above being omitted. Here is another example of agreement between the Norman and Saxon arches and pillars, which proves the correctness of their respective proportions, and that the strength of both is equal.

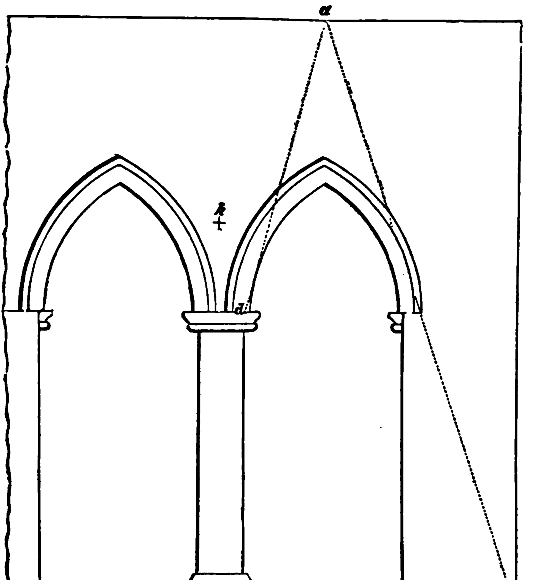
The dotted straight line *a d* falls a small distance from the inside edge of the pier, at the point *d*.

In consequence of the result of the experiments relative to figs. 60 and 61 (pp. 58, 59), a doubt arose as to the truth of 29 ft. 10 in., or say 30 ft., being the balancing height of the Norman pillar, or pier, and arch. To determine this point, the model of the pier employed was 6 in. square at the base, and 36 in. for the balancing height; because 5 ft. in 30 ft. goes six times. The arch, composed of voussoirs only, when placed on this pillar, balanced with 5 lb. on the crown; therefore, proving the balancing height to be far above 36 in., it being, indeed, 96 in., and consequently, in proportion, 30 ft.; the supposed balancing height of the Norman pillars is within the true height in the same proportion. The experiments relative to figs. 58, 59, 60, and 61 (pp. 56, 57, 58, 59), confirm these remarks. Hence, the conclusion which may be drawn is, that the calculations made to preserve the true proportions between the diameter of a pillar, its height, and the span of the arch, are not correct when the diameter of a pillar becomes one third or one half of the span.

Of the Arches and Pillars belonging to the Chapel on the North Side of the Choir of Rochester Cathedral.— The particulars are as follows (fig. 94):—

The span between the pillar and pier is 10 ft. The height of the pillar is 18 ft. The height of the shaft is 15 ft. 6 in. The diameter of the pillar, which is circular,

94



is 3 ft. The height of the masonry above the arches, taken from the intrados, is 10 ft.: above this there are other arches, &c.

In 10 ft. there are 120 in., which, divided by 6, gives 20 in. for the true diameter of the pillar; but it is 3 ft. in diameter, or 36 in., and therefore 16 in. beyond the true diameter. These 16 in. will allow 8 ft. to be added to the span for the height of the pillar, which, therefore, should

be 18 ft. The height, however, is 18 ft. 6 in., and, consequently, only 6 in. over the true dimensions.

It has been shown, when treating of the Norman and Saxon arches and pillars, that, when the diameter of a pillar is greater than one sixth of the span, the balancing height is above that which the usual calculations admit of; therefore, in this instance, it exceeds the proportion of six times the diameter.

Now, as 3 is to 10, so is 4 to 13. On looking at the experiment relative to fig. 58, the base of the pillar is 4 in. square, and it balanced the pointed arch on 32 in. in height, or eight times the diameter. Since this experiment is the nearest of any of the other experiments to the proportions of the arches and pillars under consideration, the balancing height of this pillar and arches may be fixed not far from the point *h*, which is eight diameters. I must not omit to state, in justification of the stoutness of this pillar, and those of the Norman and Saxon arches, that they have to support a superstructure of both arches and masonry; consequently, they require increased dimensions above those which were shown to be adopted in the structures of common churches.

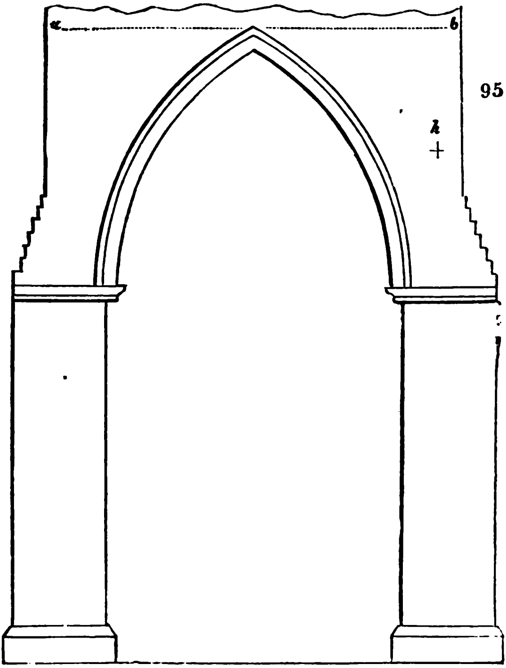
The dotted straight line *a d* falls on the inside edge of the pillar, at the point *d*; and the dotted straight line *a b* lies within the masonry, from *a* to *b*.

Of the Pillars and Arches which support one Side of the great Tower fronting the Nave in Rochester Cathedral.— Fig. 95 represents this part of the building: the width from *a* to *b* is assumed. The particulars of its dimensions are as follows:—

The span between the pillars is 26 ft. The height of the pillars is 32 ft. The height of the shafts is 28 ft. The diameter of the pillars is 8 ft. The pillars are square, and are placed diagonally to the thrust of the arch. The height of the masonry above the arch is about 83 ft.

In 26 ft. there are 312 in., which, being divided by 6,

gives 52 in. for the true diameter of the pillars. The pillars supporting this arch are square, and are placed



diagonally to the thrust of the arch, as before observed. This diagonal diameter is 8 ft., and a square having a 4 in. side gives $5\frac{1}{2}$ in., or a trifle more, for the diagonal diameter; therefore, with this proportion, the square to the 8 ft. diagonal is readily found. For 4 is to $5\frac{1}{2}$ as 8 halves are to 11 halves: again, 11 is to 8 as 8 is to 5 ft. 10 in., the square required.

Now, 5 ft. 10 in. contain 70 in., which is 18 in. above 52, the true diameter; and will therefore allow 9 ft. to be added to the height of the pillars above the span, making the true height 35 ft., or six times 5 ft. 10 in.: but the

pillars are 32 ft., therefore 3 ft. short of the balancing proportion; and they are considered with their square sides to the thrust of the arch. They, however, are placed diagonally; and, according to experiment, the balancing point is raised, in consequence, up to the point *h*, which is one fourth higher than the square side admits of. The experiment was conducted as follows, the scale being 1 in. to a foot:—

As 5 ft. 10 in., or 6 ft. (the diameter), are to 26 ft. (the span), so are 4 in. (diameter), to 17 in. (span), which is nearly enough.

Now, 35 ft. is the balancing height of the pillars under this arch, which supports one side of the tower of this cathedral; and 4 multiplied by 6 gives 24 in. for the balancing height under the arch of 17 in. span between the pillars, the arch being 16 in. span. The experiment confirmed this; for a 17 in. span, between the pillars of 24 in. in height, just balanced a Gothic arch of 16 in. span, when the pillars stood square with the thrust of the arch; and upon turning these pillars from the square to the diagonal, with the thrust of the arch, they just balanced when they were raised 6 in. higher, or from 24 in. to 30 in., which is one fourth above the original height of 24 in.

The pillars and arch of this one side of the tower have to support a height of masonry above the arch equal to 83 ft.; the total height of the tower, according to *Hasted*, being 136 ft.

As respects the stability of this part of the structure, it may be observed, that, by having the above height of masonry over the arch, it preserves the arch, as well as the pillars, from flying out, as shown by experiments in the foregoing Essays. Again, the tower being placed in the centre of the cathedral, the cross walls and arches become immovable buttresses to its four arches and pillars. And, lastly, in consequence of the four pillars being placed at *the four angles* of the square of the tower, the arches act

with considerably less overturning force against each pillar, as also shown by former experiments.

From all these circumstances, the stability of the pillars and arches, and, consequently, of the tower itself, is placed beyond the least doubt: but yet, on an inspection of the arch fronting the nave, the joints near the keystone have somewhat opened. This proves that the arch is giving way; and, as it has been shown that it could not have proceeded from any lateral yielding, it must then be from a perpendicular sinking in the foundation of one of the pillars. An evil of this kind is often occasioned by the digging of graves for the dead in our sacred temples, which must ever tend to the destruction of these buildings, and, at the same time, endanger the health of the living.

ESSAY X.

RELATIVE TO THE ARCHITECTURE OF CHURCHES AND CATHEDRALS.

King's College Chapel, Cambridge. — This structure, which is the most magnificent of its kind, is the next to be taken into consideration. With all its beauty, with all its superb sculpture and roof, and with all its sublimity, it is really a simple building, being in form a parallelogram, whose two side walls support a strong roof. Now, the objects of inquiry are, first, the dimensions and proportions of the stone roof; next, the side walls, and buttresses supporting the same.

The annexed plan (fig. 96), which has been derived from the plans and drawings of Mr. Britton, to whom every lover of church and cathedral architecture is greatly indebted, gives a vertical section of the building, at right

angles to the sides. The particulars of the dimensions are as follows: —

The span between the wall piers is 43 feet. The height of the wall to the springing is 64 ft. The thickness of the wall pier, at x, is 9 ft. The width of the pier is 4 ft. The thickness of the voussoirs and masonry of the arches, every thing included, varies from 4 in. to 6 in. between the ribs, and from 18 in. to 4 ft. at the other parts. The arch of the roof is of the elliptic form, and is supported by buttresses; consequently, the proportions and calculations, as respects *one sixth*, are here inapplicable. The buttresses being all similar and equal, any one of them will be sufficient for examination.

The thickness and height of one of these buttresses, at each set off, beginning from the springing of the arch, are as follows, and the dimensions are compared with those of the buttress represented by fig. 29, p. 30.

Buttress of King's College.		Buttress shown by Fig. 29, p. 30.	
Thickness.	Height.	Thickness.	Height.
9 ft.	4 ft.	— ft.	— ft.
13	20	4	3
17	20	6	6
21	20	8	12

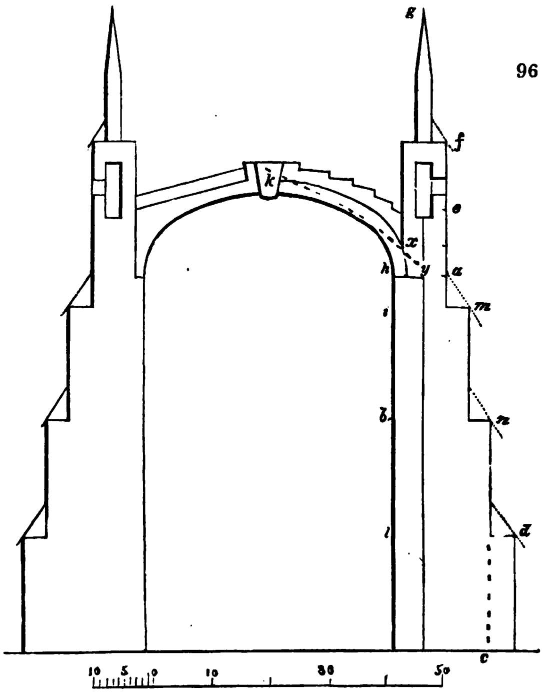
The above shows that these two buttresses differ.

In order to try the result of experiment, a model was made, on the scale of half an inch to a foot, of the chapel buttress, omitting, however, the lower part, *c d* in the diagram, when the proportions became as follows: —

Thickness.	Height.	Remarks.
9 ft. 13 17	4 ft. 20 40	These proportions nearly correspond with those of Fig. 29 (p. 30), with the exception that the height ought to be 10 ft., instead of 4 ft., at the first set off.

When a lateral force was applied at *h a*, it required the masonry to be raised 12 ft.. or 6 in. in the model, before it

96



caused the buttress to revolve on *b n*; since, with any weight less than this, the part of the buttress *h m* revolved only on the set off at *i m*. On applying the lateral force at *x*, which is 10 ft. above *i m*, the masonry was required to be raised as in fig. 29 (p. 30), and, indeed, higher, before the lateral force caused the part of the buttress *x b* to revolve on *b n*, or the whole buttress (*x c*) to revolve on the foundation (*c*). Upon adding the part *d c* to the buttress, thus completing the model of the chapel buttress, and applying the lateral force at *h a*, it required more than

twice the weight of the buttress, contained between *a* and *c*, before it would revolve on the base (*l d*). The same precise result ensued with the experiment above referred to (in p. 30), upon adding the part *k f* to it. Consequently, the part of the buttress *d c*, or *k f*, does not give any strength to the upper part of the buttress contained between *x* and *b n*.

These buttresses, throughout the building, are 23 ft. 6 in. apart, taken from centre to centre of each; and the masonry of the wall extends 4 ft. 3 in. on each side of every buttress to the window between, which is 15 ft. span. From this it is evident that each buttress has to support 23 ft. 6 in. in length of the stone roof, and only 4 ft. wide of it; or one sixth is directly supported by the buttress, which is just 4 ft.; consequently, the remaining part (19 ft. 6 in.) acts as a positive weight, the thrust continuing the same, on the 4 ft. wide arch immediately resting on the buttress; and, therefore, the lighter this 19 ft. 6 in. of arch roof is constructed, provided it be of sufficient strength, the less is the quantity of materials required. To this the architects of the chapel paid due attention, since the thickness of the masonry and arch is only from 4 in. to 6 in., where the ribs do not intervene.

Upon erecting a model arch, on the scale of half an inch to a foot, and the 19 ft. 6 in. in length being assumed at 2 ft. average thickness, it was placed on that part of the buttress comprehended between the letters *a b*, and it balanced firmly. The arch had been placed, previously, on the pier as high as *x*; but the buttress gave way on *b n*. The part of the structure *a e* equals the height of 12 ft.; and this height of masonry was found necessary, as before shown, to cause the buttress, by the lateral force, to revolve on the base (*b n* or *n*). The part *e f* also equals 12 ft., and may be considered all solid masonry, if the pinnacle *f g* above be allowed to make up for the hollow parts. On erecting these (*f e* and *e a*) upon *h a*, from where the arch springs, the

arch then balanced with two thirds of *f a* on the crown, equalling a half pound weight; and when the two side window arches were erected, abutting against the roof arch at the springing, and on the same pier (*a b*), with the masonry above completed, the roof arch balanced firmly with $2\frac{1}{2}$ lb. This weight of $2\frac{1}{2}$ lb equals more than twice the weight of the pinnacle or masonry (*a g*), and, at 17 tons to half a pound, equals 85 tons, which is strength quite ample for the security of the roof.

On the buttress, at *h a*, there is the masonry above, equalling *a f*; likewise the weight arising from the two side window arches with the incumbent masonry, which, together, fully equals the necessary part of the pinnacle above *f*, to cause the buttress, omitting the part *d c*, to revolve on the base line *c*, when a sufficient lateral force is applied at *h a* or *x*.

It has been shown, by the late experiments, that, in consequence of adding *d c* to the buttress, a greater weight than the pinnacle is absolutely requisite, before the buttress will revolve on the base (*c*); and, since all the weights above enumerated are less than twice the weight of the buttress contained between *a* and *c*, it will therefore still revolve on the base line *b n*, when an overturning lateral force is applied at *h a* or *x*; consequently, the part of the buttress *d c*, does not give any strength to the upper part of the buttress contained between *x a b n*. The extra strength caused by the addition of *d c* to all the buttresses is useful towards preserving the stability of the fabric against the shocks of tempests. The pinnacle at *g*, in the building, is raised to within a trifle of the height of the true proportions of the buttress, as given in experiment, fig. 29. Essay III., when a lateral force is to be applied to the point *x*; which is 10 ft. above the set off. Now, the point *x* is 3 ft. above where a straight line may be drawn from *k* to *y*, just within the voussoirs and masonry.

The weight of the timber roof, covered with lead, has

not been taken into consideration; but the circumstance of its being tied together by strong beams, crossing from buttress to buttress, and having perpendicular beams placed under these towards each extremity, resting on corbels issuing from the wall, just above the lowest extrados of the roof arch, causes little or no outward pressure. The side walls, as has been before stated, are 5 ft. in thickness, and the buttresses are 4 ft. wide by 21 ft. through at the bottom. Now, this proportion gives the greatest strength with the least quantity of materials, as shown by figs. 22, 23, and 24. The round towers at the four angles of this building perform the port of buttresses; they give variety, and add extreme beauty, to the chapel.

It appears, from the above inquiries, that the architect of this justly celebrated chapel, being perfectly aware of the law of buttresses, constructed a pier which would safely balance with an elliptic arch, and proper proportions of roof upon it. This being found, the lower parts of the buttress followed, of course, with the masonry above, and the pinnacle (*a g*), as in fig. 29. The lowest part (*d c*) relieved the great height (*c n*), completed the pyramidal form, and added resistance to any lateral motion of the whole building on the foundation. The spaces left between the buttresses afforded room for convenient ante-chapels, libraries, &c.

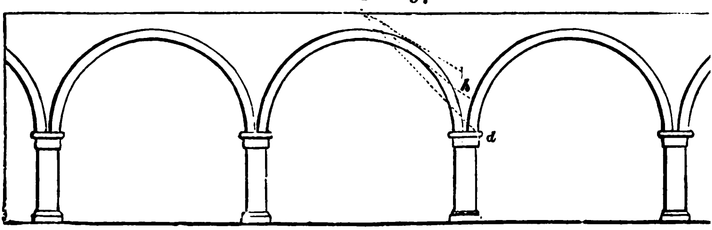
On inspecting Mr. Britton's work, or the building itself, it will be seen that each buttress at *a* forms the centre of its respective proportions of the stone roof, from which the ribs extend after the manner of radii, and through these ribs other ribs pass concentrically. The forces of all these are reduced to two straight lines, one of which runs through the centre of the whole roof, and parallel with the line of buttresses, and the other at right angles to the first line, and extending across from pier to pier, or from buttress to buttress. The keystone, which is of great weight, is placed *in the centre of* every four buttresses, and is most essential,

not only as a wedge, but, from its great weight, locking up, as it were, the lighter parts of the roof in perfect safety against being displaced by the fortuitous pressure of any person's foot.

Canterbury Cathedral.—Fig. 97 represents three arches, with their pillars, being part of the under croft of this cathedral. The particulars of the dimensions are as follows: —

The span between the pillars is 13 ft. 5 in. The height of the pillars is 6 ft. 1 in. The height of the shaft is

97



4 ft. 6 in. The diameter of the pillars is 1 ft. 3 in. The arches are semicircular.

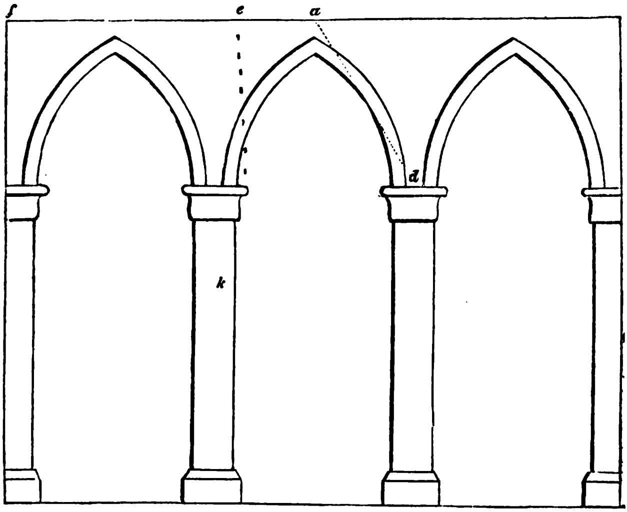
In 13 ft. 5 in. there are 161 in., which, divided by 6, gives nearly 27 in. for the true diameter of the pillars. The diameter of these pillars is, however, 15 in., therefore 12 in. within the balancing proportion; and, in consequence, a reduction of 6 ft. from the dimensions of the span is necessary to restore the height to the balancing proportion. Now, 6 ft. from 13 ft. 5 in. leaves 7 ft. 5 in., which would be the true height to support equilateral Gothic arches: but the present are Roman arches, and, therefore, they require each pillar to be reduced one fourth part lower, as shown by the experiments relative to figs. 54 and 55 (p. 53.: and this fourth part would lower the height to 5 ft. 7 in. The pillars are, however, 6 ft. 1 in.; therefore they exceed the true balancing height by 6 in.

It has been before shown, when treating of the under

croft of Rochester Cathedral, that pillars supporting four arches, two of which are at right angles to the other two will carry twice the weight that two other arches can support. The excess, then, of 6 in. in the height of each pillar may be considered as nothing. The masonry through the arches to the surface of the pavement above is about 2 ft. in thickness. In these semicircular arches the dotted straight line *a d* falls quite without the intrados; but the dotted line *a h* to the point *h* falls quite within the solid masonry; and *h* is the point of the greatest lateral resistance of the semicircular arch, as shown by the second experiment in Essay I. (p. 6.)

North Aisle of Canterbury Cathedral. — Fig. 98 repre-

98



sents three arches and piers of this part of the building. The particulars of the dimensions are as follows: —

The span between the pillars is 11 ft. 4 in. The height of the pillars is 22 ft. 8 in. The height of the shafts is

18 ft. The diameter of the pillars is 2 ft. 10 in. The thickness of the masonry, from the intrados to the top, is 3 ft.

The span, divided by 6, gives 22½ in. for the true diameter of a pillar whose height equals 11 ft. 4 in. In the case before us, the height of the pillars is double that of the span, and their diameter exceeds the true one by 12 in.: this will allow only of the addition of 6 ft., thus making the height 17 ft. 4 in.: the height of the pillar, however, exceeds this by 5 ft. 4 in. Now, putting one of these pillars, as *k*, to experimental trial, with the arch and masonry above, as shown by the dotted lines beneath *e f*, the result proved the instability of the fabric, the pillar being too slight to support the outward thrust of the incumbent arch and masonry. The structure, on inspection, appears quite strong; and the cause, the having as buttresses two of the piers of Bell Harry Tower at one end, and extra masonry at the other. Without these supports, a part, at least, if not the whole, would fall, unless retained by the superior strength of the mortar.

The dotted straight line *a d* falls on the centre of the pillar at the point *d*.

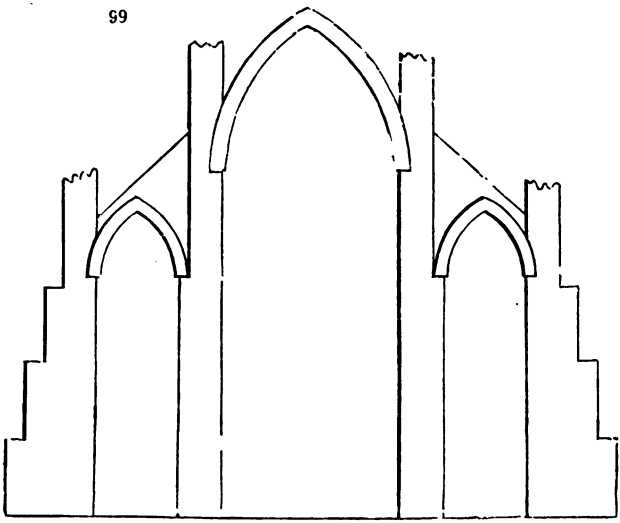
Of the Nave of Canterbury Cathedral. — Fig. 99 represents this part of the building. The particulars of the dimensions are as follow: —

The span between the pillars is 28 ft. 2 in. The height of the pillars is about 56 ft. The diameter of the pillars is 5 ft.; but they are square, and placed diagonally against the outward force of the arched roof, and, in consequence, the diagonal line is greater, being 7 ft. These pillars support two arched roofs in one direction, and arches from pillar to pillar in the other direction, which is at right angles to the first.

In the span of 28 ft. 2 in. there are 338 in., which, divided by 6, gives 56 in., and a little over, or 4 ft. 8 in. for the true diameter: but the diameter is 5 ft., or, rather, if taken

anglewise, may be considered 7 ft., therefore, one fourth of the span. These dimensions agree in their proportions

99



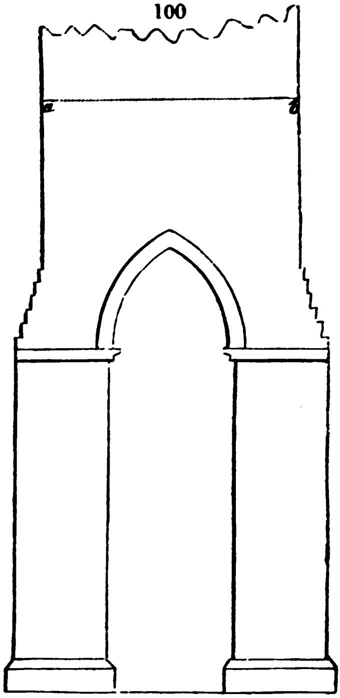
with the pillars and arches of the north aisle, and of course with the like results. The buttresses, in this instance, are two of the piers of Bell Harry Tower, and two also of those belonging to the west end towers.

It must be here observed that these pillars of the nave have the benefit of two stone roofs, acting, as before observed, at right angles to the line of the arches, and, in consequence, greatly contributing to the stability of this splendid and grove-like structure.

Of Bell Harry Tower in Canterbury Cathedral. — Fig. 100 represents a part of the tower, the particulars of the dimensions of which are as follows : —

The span between the pillars is 19 ft. 9 in. The height of the pillars is 58 ft. The diameter of the pillars, which are square, is 12 ft. ; but, being placed diagonally to the force, they equal 16 ft. 6 in. The height of the masonry,

or the tower, above the crown of the arch, is 162 ft. The total height of the tower from the ground is 237 ft.



The span of the arch is 19 ft. 9 in., or 237 in., which, divided by 6, gives 39½ in. for the true balancing diameter of pillars equalling in height the span of the arch. In this instance under consideration, these pillars are 12 ft. square; but, their being placed diagonally to the thrust of the arch, the diameter may be said to be equal to 16 ft. 6 in.; and their height is 58 ft., which is very nearly three times the span. These dimensions being beyond the scale, or proportion, of one sixth, the stability of the tower must be estimated in another way.

Now, in the experiment shown by fig. 60. (p. 58), the pillar employed is 6 in. square, with the span of the incumbent arch, $11\frac{1}{2}$ in.; but let us say 12 in. In the first place, then, as 6 ft. (diameter) is to 12 ft (span), so is 12 ft. (diameter) to 24 ft. (span): again, as 6 ft. (diameter) is to 10 ft. (span), so is 12 ft. (diameter) to 20 ft. (span).

In the first of these proportions, the span of the arch is given at 24 ft., which is too much by 4 ft.; and, in the second, the span is 20 ft., which is nearly enough; but, then, the dimensions of 10, being substituted for $11\frac{1}{2}$ or 12, is too small: the truth, it will be admitted, lies between the two.

In the experiment relative to fig. 60 (p. 58), the balancing height is shown to be 16 times 6, and, if taken at 12 for the span, equals 8 times 12. The pillars of this tower are in height 58 ft., which is not quite three times the span; they are, therefore, far within the balancing proportion. Again, as they are placed diagonally, their stability is increased a quarter part, as shown by Rochester Tower; consequently, the balancing height of these pillars to this span of arch may be considered as 10 times the span: but they are not one third part of this; and, therefore, their stability is undoubted. This tower, like that of Rochester is situated in the centre of the cathedral, and is, in like manner, supported by the walls and arches forming the cross, which act at right angles to the forces of the four arches which carry the tower.

Having now given the nature of the stability of the towers of both Rochester and Canterbury cathedrals, it may not be amiss, perhaps, to compare the two together.

Rochester Tower.	ft. in.	Canterbury Tower.	ft. in.	Difference. ft. in.	In favour of
Span of the arch . . .	26 0	Span of the arch	19 9	6 3	Canterbury.
Height of the pillars . .	32 0	Ditto . . .	58 0	26 0	Rochester.
Diameter of ditto . . .	5 10	Ditto . . .	12 0	6 2	Canterbury.
Height of the tower above the arch .	83 0	Ditto . . .	162 0	79 0	Rochester.
The squares of the bases of the four pillars of the tower equal, at 6 ft. square each, 144 ft. square as the foundation base.		The squares of the bases of the four pillars of the tower equal at 12 ft. square each, 576 ft. square as the foundation base.		432 0	Cant rbury.

Now, to exhibit the stability of these towers more clearly, the proportions of each are arranged as follows : —

Particulars.	Rochester.		Canterbury.	In favour of Rochester.	In favour of Canterbury.
The span we will call equal, or, as . . .	1	is to	1	0	0
Height of pillars to balance, is as $\frac{3}{4}$ is to $\frac{3}{8}$, or, as	1	—	2	0	1
Diameter of pillars is as	1	—	2	0	1
Height of tower is as .	1	—	2	1	0
Foundation base is as .	1	—	4	0	3
				1	5

Or, correctly, the stability of Rochester tower is to that of Canterbury as 1 is to 2 ; and, as respects the pressure of each upon the foundations, with the double height of the tower of Canterbury, it is also as 1 is to 2. Therefore, Canterbury tower has twice the stability of that of Rochester tower, and has, likewise, twice the advantage in favour of foundation base.

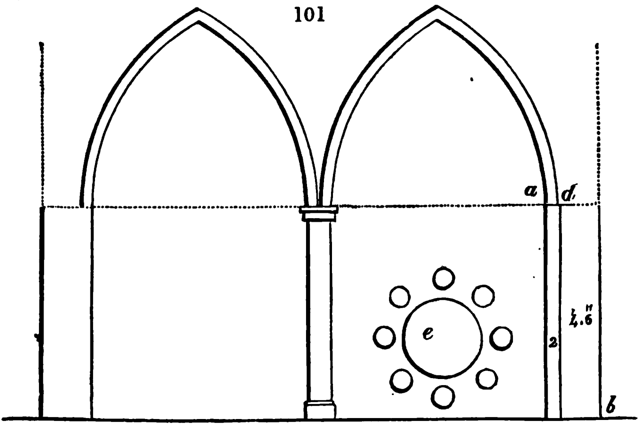
ESSAY XI.

RELATIVE TO THE ARCHITECTURE OF CHAPTER-HOUSES.

SALISBURY *Chapter-House.*— Fig. 101 represents a part of this building, which is, in form, an octagon, and its dimensions are as follows: —

The span from the pillar to the buttress wall is 27 ft. 6 in. The height of the pillar is 27 ft. 6 in. The height of the shaft is 24 ft. The diameter of the compound pillar is 2 ft. 6 in.; a horizontal section of which is shown at *e*, the large centre pillar having eight small pillars surrounding it, detached, however, at 1 in. distance. The diameter of

101



the small pillars is 4 in., and that of the large centre one is 21 in. The thickness of the wall is 2 ft. The thickness of the buttress is 4 ft. 6 in. The dimensions of the masonry over the groins and crown of the arches I do not *possess.*

Now, in 27 ft. 6 in. there are 330 in., which, divided by 6, gives 55 in. for the true balancing diameter of the pillar; but the diameter is 30 in., therefore, nearly one half part too small, when the height and span correspond. This law applies, however, to a single series of arches and pillars; but, when one pillar is placed in the centre of many arches, as in the case before us, it being eight, then, according to experiment fig. 65, p. 66, the pillar is enabled to carry double the weight of a single series: consequently, the dimensions of 30 in. rather exceeds the correct diameter.

The thickness of the wall, taken 4 ft. from the floor, is, as before stated, 2 ft.; and the buttresses, which are of the same thickness throughout, with only a small diminution from bottom to top, are each 4 ft. 6 in., making a total of 6 ft. 6 in.; but they diminish in breadth, after the height of about 10 ft., from 3 ft. 9 in., to 2 ft. 9 in., which, on the average, is 3 ft. 3 in.

The proportion which the dimensions of one whole buttress bears in its thickness to the balancing diameter is as follows:—In 6 ft. 6 in. there are 78 in., and the diameter contains 55 in.; therefore, the buttress equals one diameter and a half. The average breadth of the buttress is 3 ft. 3 in., or just half the thickness.

On submitting this building to the test of experiment by means of the buttress (*a b*), which is 6 ft. 6 in. in thickness, 3 ft. 3 in. in breadth, and from the floor to the springing in height, with a model on a scale of half an inch to a foot, the following were the results:—First, Without the side walls and window arches, and one foot of the arch *c d* placed upon the buttress, the other foot resting on a strong pier at the distance of the centre pillar, the arch thus situated balanced with $\frac{5}{8}$ lb on the top. The model buttress, as high as the springing, weighed $1\frac{1}{4}$ lb; therefore, it would support half its own weight, when placed on the crown of the arch. Secondly, Upon adding the two ad-

joining window arches, springing from the same buttress, but on opposite sides, having the octagonal inclination, and completed with masonry above from estimation only, the buttress, likewise the former arch, then balanced under the weight of $2\frac{1}{4}$ lb, which, at 17 tons to $\frac{1}{2}$ lb, equals 76 tons.

Notwithstanding all this, the structure is deficient in strength, since, on the immediate entrance into the interior, the eye is arrested, and the mind distressed, by the iron-work which radiates from the centre pillar to every buttress for its support. Yet this is the work of Sir C. Wren; and, on closely inspecting this otherwise beautiful piece of art, the cracks in the walls, and the inclination of the centre pillar, fully justified something being done for its security.

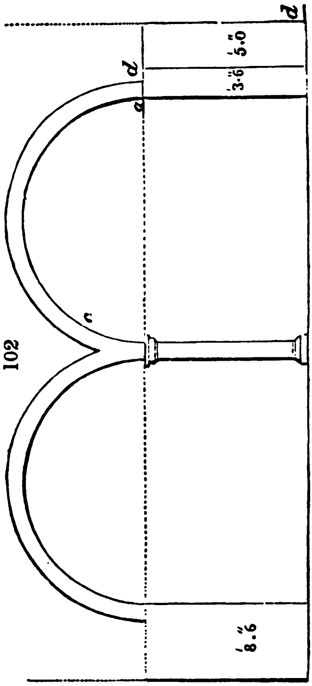
The dimensions of the buttresses appear to be not so much in fault as those of the walls, but more particularly of the centre pillar, which, being a compound one, is not equal in strength to a pillar composed of solid layers of stone. This is exactly instanced in Westminster Abbey, as may be seen on examining the pillars at the western end of the nave, and those nearest the screen. The former consist of solid layers of stone, and continue as upright as when first constructed: the latter, being compound pillars, are yielding to the pressure of the arches over the aisles; and, therefore, being similarly circumstanced to those of this chapter-house, they are obliged to be assisted in like manner by iron bars.

Worcester Chapter-House.—Fig. 102 represents a part of this building, which is a decagon, it having ten sides. The particulars of the dimensions are as follows:—

The span from the centre pillar to the buttress wall is 28 ft. The height of the pillar is 19 ft. 7 in. The height of the shaft is 17 ft. The diameter of the pillar, which is circular, is 2 ft. $4\frac{1}{2}$ in. The thickness of the wall is 3 ft. 6 in. The thickness of the buttress is 5 ft. The thickness

of the masonry over the groins and crown of the arches I do not know.

In 28 ft. there are 336 in., which, divided by 6, gives 56 in. for the balancing diameter of the pillar. The dia-



meter is, however, 28½ in., therefore one half part too small when the height equals the span; but, as in Salisbury Chapter-House, half the balancing diameter is sufficient. This pillar supports semicircular arches, consequently, the true height should be a quarter part less than the span, as shown by the experiment relative to fig 57, p. 55. Therefore, the height should be 21 ft.; but it is only 19 ft. 7 in., which is 17 in. within the balancing proportion; thus proving the

diameter of the pillar to be nearly 3 in. beyond the necessary half balancing proportion.

The total thickness through the wall and a buttress together is 8 ft. 6 in., or 102 in., which only wants 10 in. of being double of the balancing diameter. Since, however, the height of the springing is 17 in. too short, this circumstance will allow of 3 in. reduction in the diameter, thus leaving but 4 in. within the double balancing diameter. The breadth of each buttress is 2 ft. 6 in., or 30 in., which rather exceeds one quarter part of the thickness; their thickness from the ground to the top diminishes at regular distances.

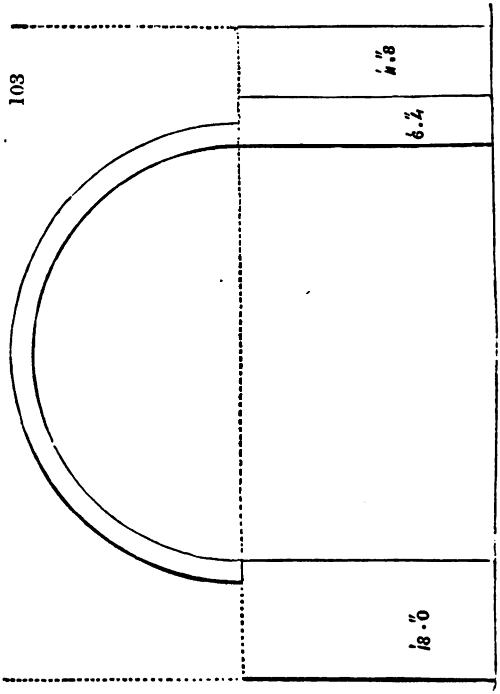
Experiment, with a model of half an inch to a foot, proved that the wall and one buttress, under the same conditions as those first mentioned relative to Salisbury Chapter-House, balanced under the weight of $\frac{3}{4}$ lb on the crown of the arch; and, under the second conditions, with the two adjoining window arches added, $2\frac{3}{4}$ lb were required to bring the buttress to the balancing point; in the latter experiment, the window arches and buttress were completed with masonry above, according to estimation. These tests gave a decided superiority of strength in favour of Worcester over Salisbury Chapter-House. This fact is confirmed by Mr. Dolvere, the verger, to whom I am particularly obliged for his kindness in sending me the dimensions, and who informed me that the building is perfectly sound.

Let me here again observe that this centre pillar is single, and composed of successive layers of stone to form one circular shaft, from the capital of which the ten several arches spring.

York Minster Chapter-House.—Fig. 103 represents a part of this building, which is in form an octagon, it having eight sides. This beautiful structure is so far different from the two former chapter-houses, that, instead of having the roof supported by a single centre pillar, it has none at

all. For the dimensions and other particulars, I am greatly indebted to Mr. Taylor, mason at the Minster, as well as for his kind offer of farther information. The dimensions are as follows:—

The span from buttress wall to buttress wall is 62 ft. 6 in.



The height to the springing is 38 ft. 3 in. The thickness of the wall is 6 ft. 4 in. The thickness of the buttress is 11 ft. 8 in.; these two latter making a total of 18 ft. The height of the masonry over the groins and crown of the arches I have not been able to ascertain.

Now 62 ft. 6 in., divided by 6, gives 10 ft. 5 in. for the balancing diameter; but the wall and buttress are together

18 ft., therefore 7 ft. 7 in. greater. The wall and buttresses support semicircular arches, which will require, as in the case of Worcester Chapter-House, a quarter part less than the span for the balancing height. The height of the springing of the arches should then be 47 ft., but the springing is 38 ft. 3 in., and, in consequence, will admit of the diameter of the pillar, but here the wall and buttress being reduced in thickness 1 ft. 5 in. allowing 2 in. in every foot of height, or one sixth, which gives for the true diameter 9 ft., and which sum doubled equals 18 ft.; thus corresponding exactly with the thickness of the wall and buttress together. The width of each buttress is 6 ft. $4\frac{1}{2}$ in., or a little above one third of the total thickness.

Under experiment, on the same scale of model as before employed, an arch placed with one foot on a buttress springing high and 18 ft. thick, having the other foot placed firmly on a block the same height, balanced with $3\frac{1}{2}$ lb on the crown. The weight of the model buttress equalled 10 lb. With the two window arches adjoining the buttresses all completed, as in the preceding chapter-houses, it then balanced under the weight of 8 lb. Mr. Taylor, in his answer to me respecting the soundness of this chapter-house, says that "the building is perfectly sound, not giving way in the least."

Upon reconsidering these chapter-houses, there appear to be three faults in the proportions of the one at Salisbury, which the other two are free from: —

First, The centre pillar, being a compound one, is not of sufficient solidity to carry the weight of the arches without yielding.

Secondly, The walls are not of that substance, being only 2 ft., to counteract any yielding of the buttresses, caused by the insufficient strength of the compound centre pillar.

Thirdly, The buttresses belonging to Salisbury Chapter-House, in the squares of their bases, possess as much ma-

terials as those of Worcester Chapter-House; but, being put together in too square a form, have not the power of counteracting the outward thrust of the incumbent arches equal to those above named, as proved by several experiments in the foregoing Essays.

Having arrived at the termination of my inquiries, and given a sufficient number of examples to illustrate my theory, I cannot close the subject without expressing my humble opinion respecting the origin of Gothic architecture; namely, that so much beauty, taste, skill, and sublimity, so far from being the work of a barbarous people, was the fruit of the accumulated industry, reflection, experience, taste, and skill of highly civilised and talented men, who were influenced in the choice of forms and ornaments not only by the climate of England, but by the religious and noble feelings of human nature.

THE END.

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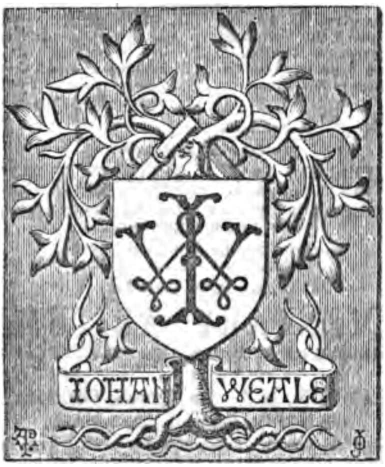
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